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Prepared for:

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THE STABILITY OF CONTROL STRUCTURES
FOR
URANIUM MILL TAILINGS

"The contents of this report may reflect the views of the contractor and not necessarily the official views or policies of the Canada Centre for Mineral and Energy Technology or the National Uranium Tailings Program"

Ottawa, September 1986

REPORT 58902 - THE STABILITY OF CONTROL STRUCTURES FOR URANIUM MILL TAILINGS

EXECUTIVE SUMMARY

This report presents a summary of a review undertaken on behalf of the National Uranium Tailings Program, NUTP, on the stability of control structures for uranium mill tailings in Canada.

Uranium tailings control structures are subject to two classes of disruptive forces:

(i) short duration extreme events such as floods, fires, earthquakes, tornadoes and glaciation which apply forces to the structures may exceed the values for which they were originally designed, and

(ii) the slow but perpetual action of forces which bring about deterioration such as water and wind erosion, the weathering and decomposition of cover and structure materials, and intrusion by roots, animals and man.

It is the objective of control structures to withstand these disruptive forces and to isolate or stabilize the tailings and soluble contaminants in the tailings impoundment. **It is an objective of impoundment close-out and abandonment preparation to have installed control structures which will remain stable and not require active care and maintenance in both the short and long term.** It is considered that current design and construction technology should be able to achieve stable structures over periods of at least 100 to 200 years. An evaluation period extending to between 1000 and 2000 years into the future was selected.

A structure is considered to have failed when release rates from it rise above some limiting value. The limiting value may be set by Regulatory Authorities or determined from an assessment of acceptable environmental impact. Structures cannot be expected to last for all time. Therefore "failure" or degradation of a structure is not a priori unacceptable. But we do need to know how structures degrade and over what time period. Then we can evaluate if this is acceptable or not.

The study comprised:

- a description of Canadian uranium tailings deposits and a review of the long term concerns relating to control structures' stability and releases

- a review and description of available technology for the evaluation of the long term stability of control structures

- application of the available technology to embankments at three generic Canadian uranium tailings sites and to the associated control structures. These generic sites were representative of:

(i) **Elliot Lake tailings deposits**
(ii) **Saskatchewan neutral tailings from low/medium grade ores**
(iii) **Saskatchewan nickel, arsenic, clay tailings from high grade ores**

- an evaluation of a range of alternative measures which may be considered for the long term stabilization of the control structures.

Evaluation of conditions at the existing sites suggested that the primary long term concerns regarding control structure stability and release rates were related to the following:

(a) Embankments

(i) Sheet, Gully and Flood erosion.
(ii) Wind erosion
(iii) Leaching/salt migration/drain clogging
(iv) Frost action
(v) Seepage erosion (or piping)
(vi) Physical instability

(b) Diversion Works

(i) Floods
(ii) Gully erosion
(iii) Ice and debris blockage
(iv) Sedimentation

(c) Surface Water Quality

(i) Impoundment surface runoff
(ii) Seepage

Of these, gully erosion was identified as a major long term stability concern while flood erosion, salt migration and drain clogging, frost action, seepage erosion and physical instability appeared to have a moderate potential for causing embankment instability.

Each of the failure mechanisms associated with diversion structures were assessed as having a high probability of occurrence.

It was identified that in order to control surface water quality, long term water treatment may be necessary at many of the tailings sites. Acid generation is one of the prime concerns and is not unique to uranium tailings impoundments. Further research in this area is required to develop long term solutions.

Following a more detailed analysis and evaluation of the control structures at the three generic sites the following conclusions were reached.

1. The climatic, tailings and site characteristics at the Canadian uranium tailings deposit are significantly different from those in the U.S.A. Significant differences occur in precipitation, frost action, radon emanation, climax vegetation and ore grade and

associated contaminants. While much of the U.S.A.-developed stability technology is of direct relevance to Canadian deposits, a different design emphasis and some different design techniques are required for Canadian conditions.

2. The climax vegetation at the deposit sites is forest. Forest cover is therefore potentially a realistic long term stable regenerative cover. It provides sheet and wind erosion control and assists in limiting infiltration, frost heave and salt migration. Forest cover permits a reduction in the thickness of other cover layers which may be used in combination with it and should be evaluated in the development of all cover and structure stabilization designs.

3. Gully erosion is a major concern for the long term stability of tailings embankments. Current technology is inadequate to demonstrate the stabilizing effect of forest cover. Riprap is the only proven demonstrable control measure for long term gully erosion prevention. Embankments constructed from coarse rock waste or with a layer of heavy riprap would be stable against long term gully erosion.

4. Wind and sheet erosion can be controlled by forest cover. Forest cover is sufficient for this purpose where embankments are constructed of or covered with coarse gravelly till or outwash soils.

5. There is a high probability of underdrains in embankments clogging at some of the impoundments due to:

   - chemical precipitation
   - root penetration
   - seepage erosion
   - frost action
   - covering of drain outlets

   Design of drains should include: filter protection; operate in a flooded condition; surplus drainage volume and discharges at locations and in a manner which prevents blockage by solifluction, sedimentation or frost.

6. Perma-frost conditions are encountered in the northern Saskatchewan impoundments where frost action is a potentially severe disruptive force. Considerably less frost action is encountered in the Elliot Lake area. Frost action can cause severe disruption of the tailings cover and surfaces of tailings embankments. Frost heave can effect diversion and drainage structures. Frost cycling will induce soil creep on steep (2:1) embankment slopes. Forest cover considerably reduces frost penetration.

7. Seepage erosion (including piping) may be a significant mechanism of embankment instability where:

   (i) embankments are constructed of rock waste with inadequate filters on the upstream side.

(ii) drain blockage occurs near the discharge resulting in high pore pressures in the embankment toe.

Such conditions were assessed as problems at two of the generic embankments evaluated.

8. A moderate to high potential risk of physical instability (slip surface failure) exists over the long term for the generic Saskatchewan embankments if decommissioned with side slopes at 2:1 without remedial measures to prevent the failure mechanisms described above.

9. Diversion works are extremely vulnerable to long term instability with a high likelihood of each mechanism of failure occurring.

   (i) Flood flows are expected to exceed the values currently commonly used for design. It is recommended that close-out diversion works be designed to accommodate the probable maximum flood (PMF).

   (ii) Severe gully erosion is anticipated unless heavy riprap scour protection is installed.

   (iii) Ice and debris blockage is anticipated. Control methodology includes installation of wide bottomed structures with sufficient flow capacity to allow partial blockage.

   (iv) Sediment accumulation in diversion structures is anticipated. A number of mitigation measures are described.

10. Surface water quality is expected to be a long term concern due to:

   (i) acid generation in the pyrite rich tailings deposits

   (ii) leaching of surface layers of tailings by shallow flows of infiltration water which mound on slime layers or low permeability tailings

   (iii) contamination with impoundment seepage water

A variety of control methodologies are defined. These include pyrite removal, and the reduction of oxidation rates by placing a soil cover, by bacteriacide, phosphates or limestone addition. The potential success of these measures could not be determined within the scope of this study. Many of the methods are still experimental and their long term effectiveness has not been established. Provision of a deep (2 to 3 m) water cover is the one acid generation stabilization measure which appears to be demonstrably effective in the long term and economic under appropriate circumstances.

This report is a summary report and is backed up by a set of five Technical Memoranda (TM) as follows:

TMI - CANADIAN URANIUM TAILINGS DEPOSITS AND STRUCTURES

TMII - CHARACTERISTICS RELEVANT TO RELEASES OF THREE GENERIC CANADIAN URANIUM TAILINGS SITES

TMIII - METHODOLOGY FOR STABILITY AND RELEASE RATE EVALUATION

TMIV - ASSESSMENT OF ALTERNATIVE EVALUATION METHODS AND ALTERNATIVE STABILIZATION PRACTICES

TMV - EVALUATION OF COVER AND STRUCTURE STABILITY ON THREE GENERIC CANADIAN URANIUM TAILINGS SITES

This study was conducted in parallel with another study entitled "THE TECHNOLOGY OF URANIUM TAILINGS COVERS" which is summarized in a report of the same title (Steffen, Robertson and Kirsten, 1986). There is considerable overlap and interdependence between structures' and covers' stability. However, the two summary reports have been written as independent documents, with the result that there is considerable duplication and repetition in the two reports.

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1.0 STABILITY OBJECTIVES OF CONTROL STRUCTURES

1.1 INTRODUCTION

This report presents a summary of the results of a review undertaken on behalf of the National Uranium Tailings Program (NUTP) on the stability of control structures for uranium mill tailings in Canada. The scope of the work was to:

1. Describe the engineering practices used in the construction of uranium tailings dams and control structures in Canada where information is available. This description was to include site selection and preparation, materials selection, construction monitoring and short-term results.

2. In consultation with the scientific authority, select four "generic" control structures that are typical of actual installations. It was envisaged that two structures would be applicable to the Elliot Lake uranium district and two applicable to active northern Saskatchewan locations. This was changed during the course of the study to three generic sites of which one was applicable to Elliot Lake conditions.

3. Describe as precisely as possible the environmental conditions (weather, biological activity) applicable to the generic structures. Include a discussion of ranges and uncertainty.

4. Conduct a literature review on the stability and failure analyses of relevant structures. Special emphasis was to be placed on Canadian conditions.

5. Conduct stability analyses of the selected cases. The analyses should include mechanisms and rates of degradation and transient behaviour within the specified time limits.

6. In consultation with the scientific authority, derive relationships that can be used to predict structure degradation and release rates of both contaminated water and tailings solids. Using these derivations and reasonable geotechnical and tailings conditions, predict release rates for the generic cases.

7. Present conceptual designs with economic analyses that significantly improve long-term stability and reduce release rates for the four cases.

This study was undertaken in combination with a similar review and evaluation of the technology of uranium tailings covers. A detailed description of the study has been presented in a series of five Technical Memoranda (TM) as follows:

TM I - Canadian Uranium Tailings Deposits and Structures

This technical memorandum provides a brief description of the environment at the location of the various Canadian uranium tailings deposits and the characteristics of the tailings and deposits. The purpose of the description is to provide a general understanding of the nature and variety of uranium tailings deposits and the conditions in which they exist. The stability of the existing tailings control structures and contaminant release rates are briefly reviewed. An assessment is made of the present and long-term potential for cover and structure instability on a purely qualitative basis.

TM II - Characteristics Relevant to Releases of Three Canadian Uranium Tailings Sites

The characteristics of the tailings deposits and retention structures for three typical but non-specific generic tailings sites are described. One site is typical of the Ontario deposits near Elliot Lake and two are typical of the Saskatchewan deposits for the following ore types:

- low/medium grade, low sulphide ores
- higher grade, high clay, nickel and arsenic ores

The evaluation studies undertaken in TM V are based on the characteristics defined for these three generic sites.

TM III - Methodology for Stability and Release Rate Evaluation

Available technology, that may be employed to evaluate the stability of uranium tailings covers and control structures, and to determine release rates, is described and reviewed.

TM IV - Assessment of Alternative Evaluation Methods and Alternative Stabilization Practices

This technical memorandum describes alternative cover technology, the assessment work done on alternative methods of long term stability evaluation and release rate estimation. In it the methodologies described in TM III are applied to typical Canadian deposits and structures with the object of determining the suitability and applicability of the technology to Canadian conditions.

TM V - Evaluation of Cover and Structure Stability on Three Generic Canadian Uranium Tailings Sites

The long term stability of the covers and structures of the three generic sites described in TM II are evaluated, with a view to identifying the failure mechanisms of greatest concern and appropriate long term stabilization measures. Characteristics of the generic sites, while typical of actual sites, are modified to allow evaluation of a wider range of long term stability concerns under a number of reclamation scenarios and do not reflect evaluations of any actual Canadian deposits.

This study was done in parallel with another entitled "The Technology of Uranium Tailings Covers" and written up in a report of the same title (Steffen, Robertson and Kirsten, 1986). The problems of stability of uranium tailings covers and structures overlap and are interdependent. Consequently the technologies are similar and there is a considerable amount of repetition in the two reports which have been prepared as separate documents.

1.2 STUDY OBJECTIVES

During the past 15 years there has been a marked increase in the concern and interest by the public, regulatory authorities and the mining industry in the environmental impact of uranium and other mine wastes. Uranium mine wastes and tailings, because of their radiological constituents, have been the focus of many of these concerns. An early reflection of public concern in Canada, and a key document in the process of Regulatory control of uranium tailings, is the Final Report of Cluff Lake Board of Enquiry (Bayda et al, 1978). This enquiry investigated the environmental impact of the Cluff Lake mine development as well as future uranium mining development in Saskatchewan. The effects of tailings and mine wastes were a major component of this enquiry.

As a consequence, considerable effort has been made by both industry and Regulatory Agencies alike to develop and implement adequate stabilization and control technology. The objective of this technology is to isolate or stabilize the tailings in the depository area. Release rates of environmental contaminants must be sufficiently low to satisfy release criteria which ensure that an acceptable level of environmental impact is achieved in both the short and the long term.

During the operating period, while tailings are being produced, manpower and equipment resources are available at the mine site to monitor the release rates. If release rates exceed specified limits, remedial action can be implemented. Following closure of the mill facilities, the tailings deposits remain as a long term potential source of radioactive materials and other environmental contaminants. The rate at which these contaminants may be released to the environment will change with time as:

(i) the tailings change their chemical and physical nature as a result of the weathering and other hydrogeochemical processes that occur, and

(ii) the containment structures are subject to physical and chemical processes which modify their ability to function in the manner in which they were originally conceived and designed.

If the rates of change are very, very small then the changes in the release rates may not be significantly different for a very long time. Small but perpetual change which results in cumulative increases in release rates may bring about unacceptable rates of release in lesser time periods. Rapid changes could result in large releases in relatively short periods.

Critical to an evaluation of the long term environmental impact of uranium tailings is the stability of both the tailings products and the containment structures. Stability is that characteristic of a material or structure

which indicates its resistance to change. A structure or material is stable if, over the period of interest, the change in it is sufficiently small not to make a significant difference to the rate of the contaminant release with which it is associated. Conversely, it is unstable if the release rate changes significantly or becomes unacceptably high.

The tailings materials themselves are metastable in that they have been crushed and placed in an environment which differs considerably from that which existed at the location of the original ores. Considerable change may occur in the physical and chemical nature of the tailings before they reach equilibrium under the conditions of this new environment.

Most of the physical and chemical change of concern to the long term stability of uranium tailings and their containment structures are relatively slow but progressive. It is necessary to know both the rate of change and the time period of interest before an assessment can be made of the long term stability of the materials and structures.

The period for which the tailings will remain as potential contaminant sources exceeds by a number of orders of magnitude, the periods for which man can economically design and construct tailings containment structures. Thus the period of interest is determined by that period over which current design and construction technology can be applied with some confidence.

At the onset of this study it was presumed that current design and construction technology should be able to achieve stable structures over periods of at least 100 to 200 years. Since the purpose of this study is to evaluate the long term stability of such structures, an evaluation period extending to between 1000 and 2000 years into the future was selected.

The main objective of this study was to identify the available technology for the evaluation of the long term stability of the structural elements of uranium tailings, then to evaluate the stability of typical Canadian structures and to identify suitable structural designs to achieve long term stability.

1.3 CONTROL STRUCTURES

1.3.1 Types of Control Structures

Uranium tailings control structures can be divided into five broad groups:

(i) Covers
(ii) Liners
(iii) Embankments
(iv) Diversion Structures
(v) Water Treatment Facilities

Of these, the first two groups have been evaluated for the NUTP in separate studies by Steffen, Robertson and Kirsten (1986) and Clifton and Associates (1986). Since there is an interdependency between the various structures, some aspects of the stability of these structures are considered also in this study. However, this study is concerned mainly with structures in

groups (iii) Embankments and (iv) Diversion Structures. The provision of water treatment facilities, in the long term, requires the continued interaction and activity of man, and stability becomes more an issue in government and institutional stability as well as economics. It is considered only to the extent that the stability of group (i) to (iv) structures dictate that long term treatment will be required.

1.3.2 Factors Effecting Stability

Embankments and diversion structures, constructed with the tailings impoundments, may be subdivided into two classifications:

(i) Those structures that were designed and constructed prior to the implementation of the present licensing and engineering review process. Some of these structures have been built to standards which would not be acceptable as good practice today. Release rates associated with these structures may currently be in excess of what is considered acceptable in the long term. Examples are the embankments in the Elliot Lake region constructed of cycloned tailings. Erosion rates and seepage through these embankments may currently imply failure against any long term contaminant criteria. It is anticipated that such structures will be improved, to satisfy stability and release rate requirements for class (ii) structures, prior to abandonment.

(ii) Those structures which have been designed and constructed to satisfy the stability and release control criteria now required for regulatory approval and to satisfy what is considered good practice. For the purposes of this study it is assumed that the required stability and release standards will not change with time; i.e., that failure occurs when a release rate rises above an unchanging limiting value, and not when a constant release rate becomes unacceptable because the limiting value of acceptable release has been lowered.

Since it is presumed that all structures satisfy the release rate control criteria required of them at the time of abandonment, failure can only occur if there is a change which results in increased releases.

Changes can occur as a result of short term extreme events such as floods, fires, droughts, earthquakes, etc., which exceed in magnitude the events for which the structures were designed. Change can also occur as a result of the slow but perpetual action of factors which bring about deterioration such as erosion, weathering and leaching.

Some of the major factors influencing the long term stability of structures are summarized below.

A. Extreme Events

(i) High precipitation (floods - wet periods)
(ii) High winds (tornadoes, cyclones)
(iii) Earthquakes
(iv) Forest fires
(v) Extreme frost

B. Time Dependent Degradation

(a) Surface Mechanisms

(i) Sheet erosion
(ii) Gully erosion
(iii) Sedimentation, ice and debris blockage
(iv) Biological penetration

(b) Subsurface Mechanisms

(v) Frost action
(vi) Increased groundwater table
(vii) Weathering and degradation
(viii) Leaching and seepage
(ix) Precipitation and drain clogging

In this study the effects of each of these factors on structure stability are reviewed, and evaluation and design methodology is described and applied to typical Canadian structures.

Failure could result in increased releases in the form of:

- particulate dispersion
- contaminated seepage
- radon emanation
- direct radiation

1.4 EVALUATION FOR CANADIAN CONDITIONS

1.4.1 Characteristics of Canadian Deposits

Sources of available technology for cover design have been reviewed in section III.1.2 of Technical Memorandum III. Much of available technology and recommended design methodology is based on research undertaken in the United States of America as a consequence of the U.S. Congress enactment of November 1978 entitled the Uranium Mill Tailings Radiation Control Act. The standards, guidelines and recommendations resulting from this research are suited to the ore types, climatic conditions, problems and concerns typical of the U.S.A. uranium tailings deposits.

These conditions are materially different from those applicable to the Canadian uranium tailings deposits. A direct transfer of the methods and guidelines, developed for the U.S. deposits, to the Canadian deposits is inappropriate. However, much of what has been done in the U.S.A. and elsewhere is of direct relevance, or can be modified to be applicable, to Canadian deposits.

In order to identify these differences, a review was made of all Canadian uranium tailings deposits and a description developed of each of the deposits. This description is presented in Technical Memorandum I.

Almost all of the Canadian uranium tailings deposits are located in deposits in two geographical areas. Approximately 100 million tons of tailings from 13 mines and 11 mills have been produced and placed in 10 deposits in the Elliot Lake region of Ontario. The location of these tailings areas are shown on Figure 1. The second major uranium mineral belt occurs in northern Saskatchewan where 10 mines (now all decommissioned) operated in the Uranium City area, and three new mines have been started since 1975 at Cluff Lake, Rabbit Lake and Key Lake. All these deposits are located north of the 57th parallel as shown on Figure 2.

Some of the major differences between typical Canadian and typical U.S.A. deposits are reviewed below.

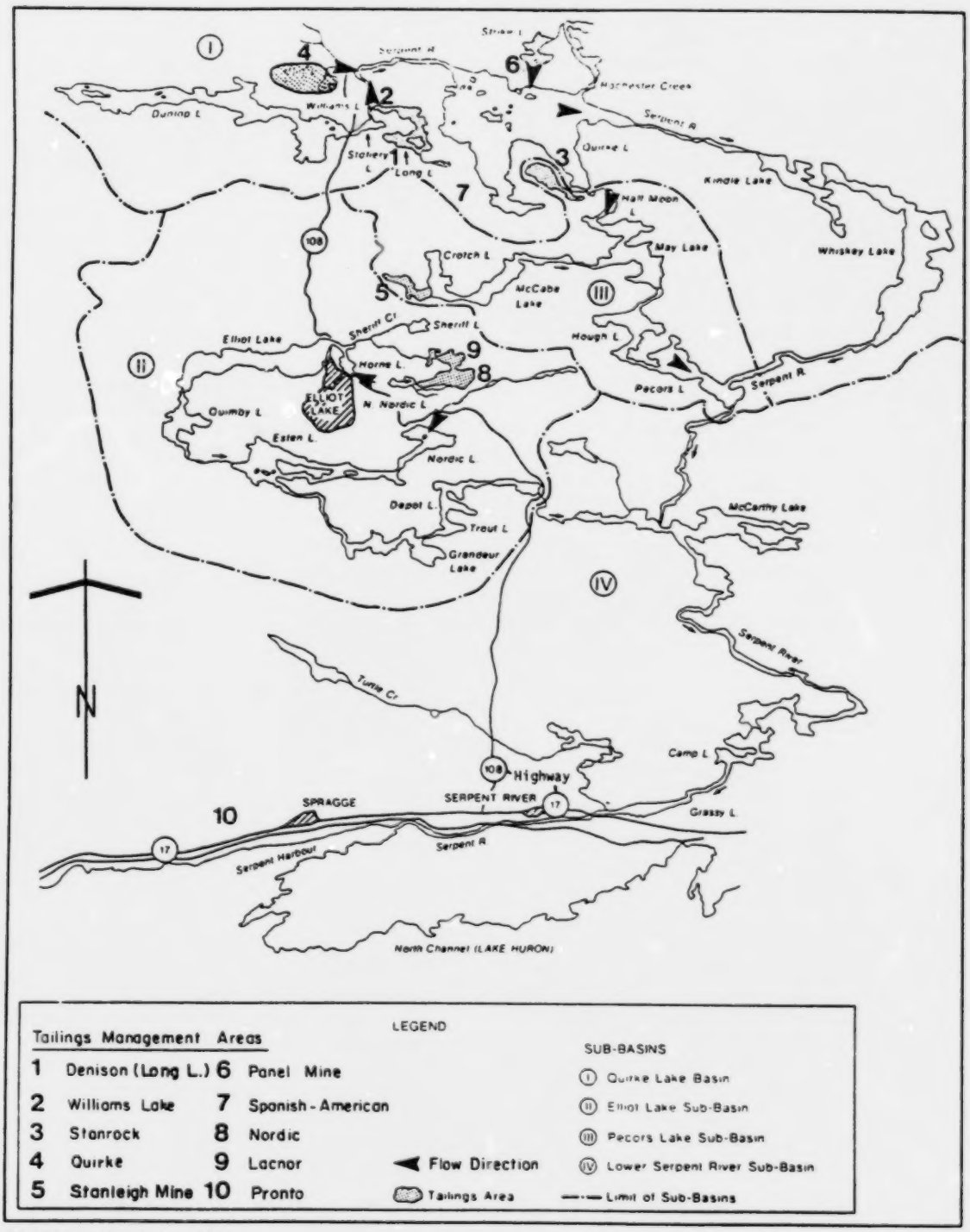
(i) The topography and geomorphology for all Canadian sites (described in I.2.1 of TM I) is fairly similar as both areas are located on the Canadian Shield. The topography is characterized by bedrock knolls and ridges separated by lower areas consisting of numerous lakes and swamps. While the bedrock geology differs in the various areas, there is generally only a shallow surficial cover of glacial tills and outwash sands, with recent organic deposits (muskegs). These areas are generally deficient in clay deposits. This contrasts strongly with most of the U.S.A. deposit areas where deep soils often overly the bedrock. The soils are rich in clay minerals and therefore have a high ion exchange capacity, making them very active retardants of many forms of contaminants in the tailings seepage water.

(ii) The water table at the Canadian sites is generally shallow. Infiltration and seepage is generally very active (short seepage path lengths and rapid seepage) and the ground and surface waters are of a high quality with a low concentration of dissolved solids. This contrasts with typical U.S.A. sites where groundwater tables are often at depth with low rates of recharge and seepage migration. Thus the impact of contaminated seepage from U.S.A. deposits are typically considerably less than from Canadian deposits.

(iii) An excess of precipitation over evaporation occurs in the Elliot Lake region compared with deficits in Saskatchewan and most of the U.S.A. deposit areas (Refer I.2.2). The design of zero discharge systems are therefore not possible at Elliot Lake. If runoff and seepage from Canadian deposits cannot be improved to a quality allowing discharge to surrounding surface waters, then long term water treatment will be required.

(iv) Infiltration and soil moisture is generally considerably greater for the Canadian sites than for U.S. deposits. This has beneficial effects:

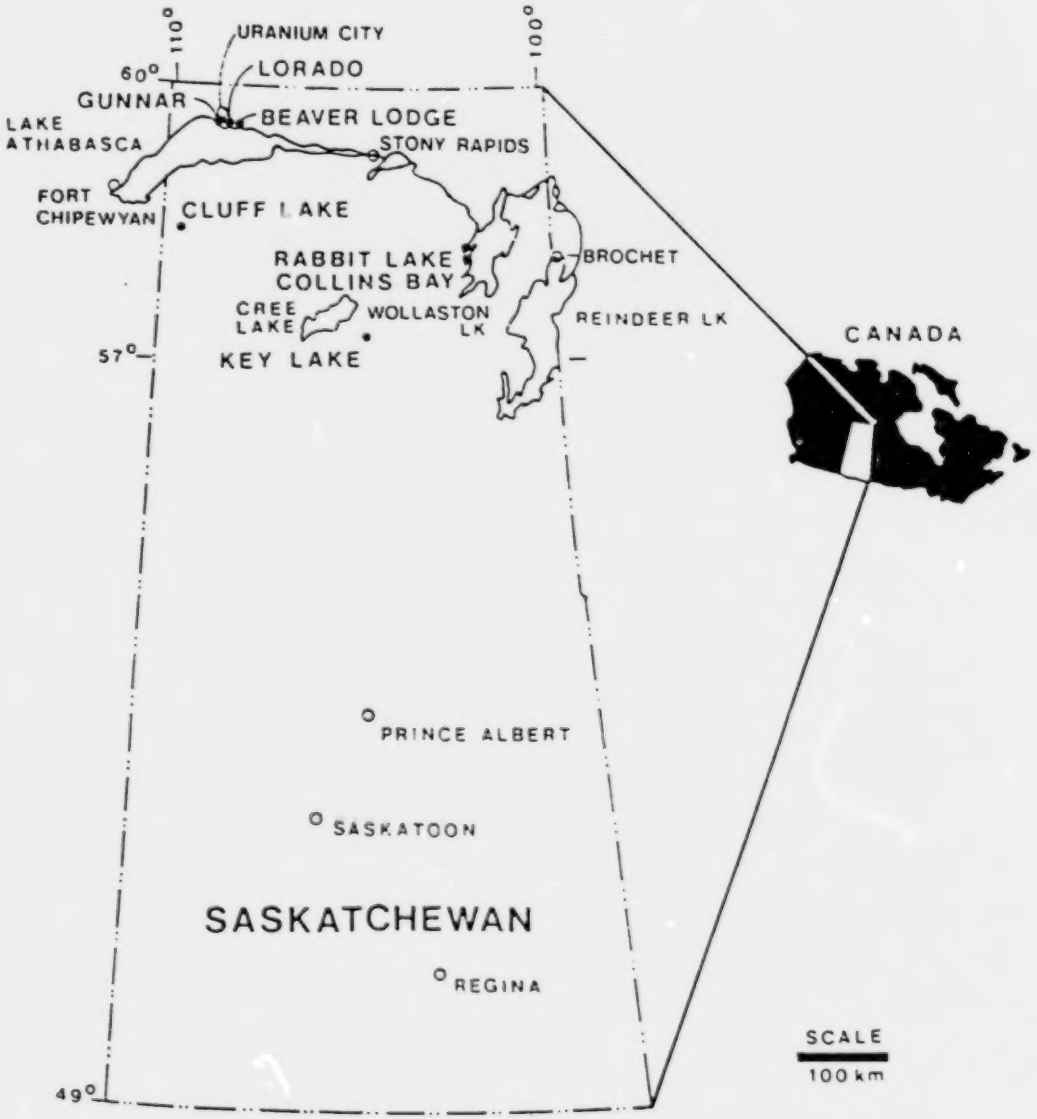
- The increased soil moisture results in decreased radon emanation rates (refer section IV.1.4). Radon emanation rates (for equivalent tailings deposits) are considerably less in Canada than the U.S.A. and therefore of less concern.



SOURCE - Marshall, 1982

TAILINGS MANAGEMENT AREAS, ELLIOT LAKE, ONTARIO

FIGURE 1



TAILINGS MANAGEMENT AREAS, SASKATCHEWAN

FIGURE 2

- Vegetation can be more easily established than in the drier U.S.A. deposit areas.

It also has disadvantages:

- All infiltration becomes contaminated and must emerge as contaminated seepage.

- Mounding of the water table occurs in some impoundments resulting in flooding (and vegetation kill) as well as upward leaching and salt migration. Filter drains in embankments may have to remain effective to ensure embankment stability in the long term.

(v) Greater frost potential and freezing depths occur at the Canadian sites. Discontinuous permafrost conditions exist at all the Saskatchewan sites, where frost heave and permafrost aggradation or degradation is a potential cause of embankment instability. Surface freezing and ice accumulation also reduces radon emanation.

(vi) Forest type vegetative covers are characteristic of both the Elliot Lake and Saskatchewan tailings areas (Refer I.2.3). If similar vegetation can be established on the uranium tailings deposits then they form a much more effective erosion protection layer than can typically be achieved by the sparse grass and scrub type covers considered more typical of the U.S.A. tailings areas.

(vii) A lower incidence of burrowing animals, especially colony types, occurs in the Canadian deposit areas than in the U.S.A. (Refer I.2.4). The Canadian sites also tend to be more remote from human habitation areas (Refer I.2.5). Thus the potential for burrowing or excavation is less with a commensurately lower requirement for biotic barriers.

(viii) Ore characteristics vary greatly even between the various Canadian deposits. Three broadly different ore types can be identified in Canada (I.3.1):

(a) Lower grade ore, high pyrite tailings from the Elliot Lake ores. These tailings are acid generating resulting in both acidic seepage and salt migration. This acid generating potential makes direct revegetation problematic and requires long term seepage water control. It also results in increased loads of dissolved constituents which may precipitate out at other locations.

(b) Low/medium grade ore, non-acid generating tailings from the majority of the Saskatchewan mines. These tailings have a relatively low environmental impact potential.

(c) High grade ores, sulphide, nickel-arsenic tailings from the newest Saskatchewan mines which have acid generating potential, and relatively high environmental impact potential as a consequence of the contained radionuclides, nickel and arsenic. A higher level of isolation and contaminant security is required for these tailings than for those above, or for typical U.S. deposits.

Unlike most U.S.A. uranium tailings deposits, the Canadian tailings are generally neutralized or taken to a high pH prior to discharge. The potential for low pH conditions are therefore dependent on the acid generating potential of the tailings and the development of conditions which will result in acid generation in the deposit. Again, the potential exists for the precipitation of soluble salts (mainly gypsum) with the associated decreases in pH.

In order to identify the characteristics of Canadian deposits relevant to contaminant releases and long term stability, a summary description was prepared for most of the major deposits including 9 in the Elliot Lake area and 6 in northern Saskatchewan (refer section I.4). The materials used for construction and the construction practice used have a considerable effect on the effectiveness and long term stability of the impoundment facilities and these were summarized for various representative Canadian sites (refer section I.6).

1.4.2 Evaluation of Instability Potential at Deposit Sites

Based on the information available to the authors in the available documentation, as well as discussions with some of the deposit operators and involved persons, a qualitative assessment was made of the potential for tailings structures instability assuming that a minimal amount of reclamation is done at each site at close-out. Both present and future instability was considered. The results of this assessment (refer I.6.11) are summarized in Table 1. It should be noted that this evaluation of present or future instability does not imply that the potential for tailings releases will remain as evaluated. In many instances (including all operating impoundments) the facility operator may implement maintenance, secondary containment or alternative close-out measures which considerably modify and possibly prevent any instability or releases.

The assessments are subjective and are made without knowing what final reclamation work will be implemented. It serves to provide an assessment of those potential mechanisms of failure most likely to result in instability of Canadian uranium tailings containment structures.

From these evaluations the following conclusions were reached:

(a) For embankments:

- gully erosion is of severe concern at almost all tailings impoundments

SUMMARY OF STABILITY ASSESSMENTS FOR CANADIAN TAILINGS CONTAINMENT STRUCTURES

IMPOUNDMENT SITE	EMBANKMENTS																DIVERSION WORKS								SURFACE WATER QUALITY					
	Sheet Erosion		Gully Erosion		Flood Erosion		Wind Erosion		Salt Migration		Frost Action		Physical Instability		Piping		Floods		Gully Erosion		Ice & Debris Blockage		Sediment		Without Treatment		With Treatment		Seepage	
	P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F
A. ONTARIO SITES																														
Denison Tailings Area	m	M	M	s	n	M	m	m	n	m	N	N	m	m	n	m	m	M	m	s	m	s	m	s	s	s	m	m	n	m
Williams Lake Tailings	m	M	m	s	m	M	m	m	n	m	N	N	m	m	n	m	n	M	n	m	m	S	m	M	s	s	m	m	n	m
Stanrock Tailings Area	M	s	M	s	m	M	M	M	m	m	N	N	m	M	m	m	m	M	m	M	m	S	m	M	s	s	m	m	N	N
Quirke Tailings Area	m	M	m	M	m	M	m	m	n	m	N	N	m	m	m	M	m	s	M	s	m	M	m	M	s	s	m	m	n	m
Stanleigh Tailings Area	m	M	m	s	m	M	m	m	m	m	N	N	m	m	n	m	n	M	m	M	m	s	m	M	s	s	m	m	n	m
Panel Tailings Area	m	M	m	s	m	M	m	m	n	m	N	N	N	N	n	M	m	M	m	M	M	s	M	M	s	s	m	m	m	M
Spanish American Area	N	N	N	N	N	N	N	N	N	N	N	N	M	M	N	N	N	N	N	N	N	N	N	N	s	s	m	m	N	N
Lacnor & Nordic Tailings	m	M	m	s	m	M	m	m	m	m	N	N	M	M	n	M	M	s	M	s	M	s	M	s	s	s	m	m	N	N
B. SASKATCHEWAN SITES																														
Cluff Lake Tailings	M	M	m	M	n	m	n	s	n	s	U	M	m	m	n	M	m	s	m	M	m	s	m	s	s	s	m	m	m	m
Key Lake Tailings	M	s	s	s	n	m	m	M	n	m	n	M	m	M	n	m	m	M	m	m	m	M	m	M	s	s	m	m	m	s
Rabbit Lake Tailings	M	s	m	s	n	m	m	m	n	s	m	s	m	s	m	s	m	m	m	m	m	M	m	M	s	s	m	m	M	s
Collins Bay Tailings	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	n	n	n	n	n	n	n	n	M	M	m	m	m	m

NOTES:

(i) P = Present conditions refers to current experience for the respective mode of instability, classed as:

n - none
m - minor
M - moderate
s - severe
N - not applicable
U - unknown

(ii) F = Future potential conditions refers to the potential of releases occurring over a 200 to a 2000 year period if no extensive abandonment measures are implemented, classed as:

n - none
m - minor
M - moderate
s - severe
N - not applicable
U - unknown

(iii) Evaluations of present or future instability do not imply potential for tailings releases. Releases can be prevented by maintenance, secondary containment or implementation of alternative reclamation measures. Reclamation measures have yet to be finalized for all operating impoundments and some of the inactive impoundments.

TABLE 1

- frost action is of moderate to severe concern for embankments in Saskatchewan

- physical instability, piping failure, wind erosion and floods are of moderate concern at a number of the sites.

(b) Diversion works:

- all of the failure mechanisms are of severe or moderate concern at almost all of the impoundment sites. There appears to be a high likelihood that diversion structures will fail in the long term.

(c) Surface water quality:

- in the absence of water treatment the potential for large releases is a severe concern at most of the tailings deposit sites

- seepage is of severe concern at some Saskatchewan sites

The Collins Bay tailings impoundment, because of the nature of the containment structure has a very high degree of long term structural stability.

At Gunnar and Lorado, the tailings are not retained behind formally engineered and constructed embankments, and a stability evaluation is not applicable.

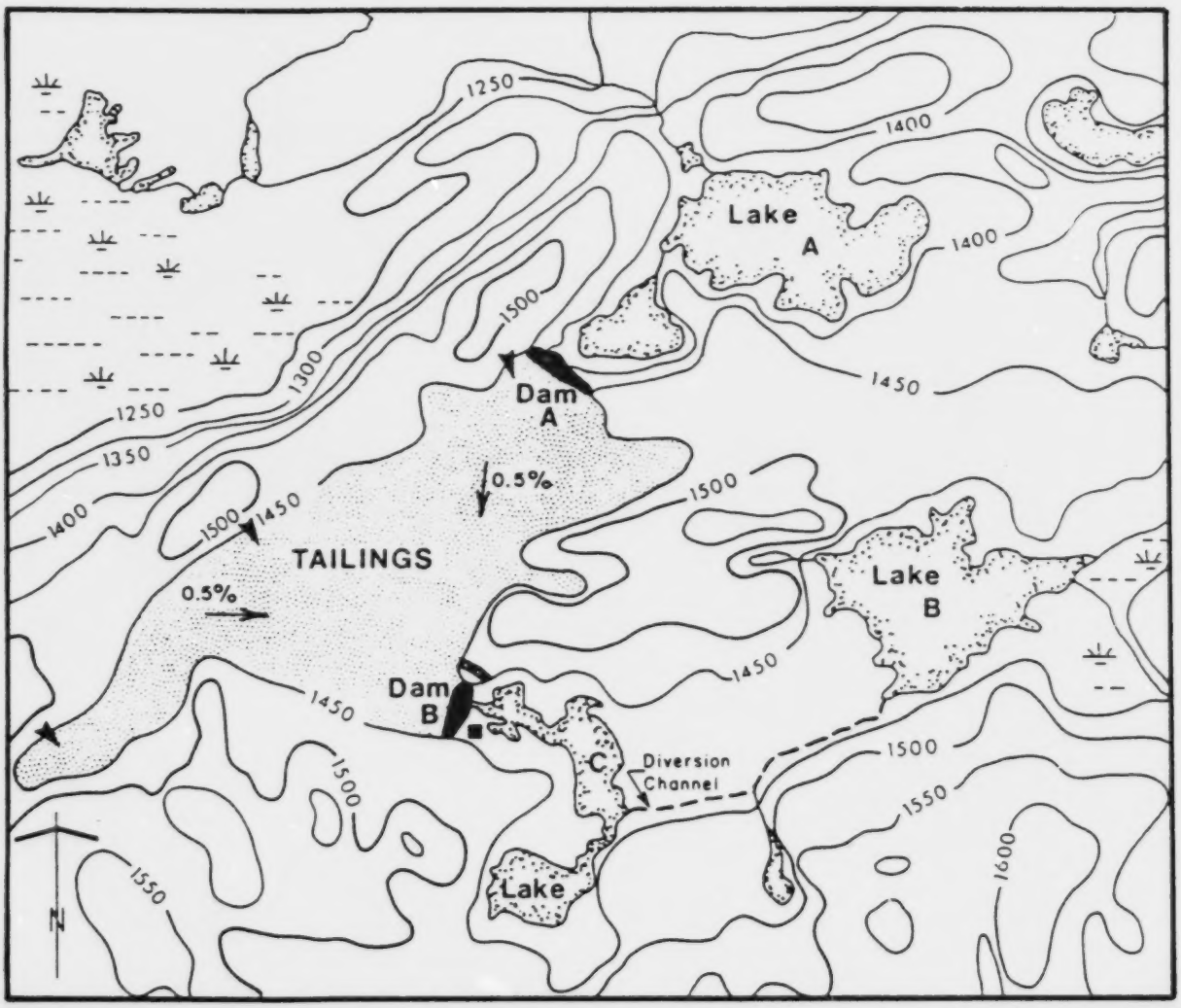
1.4.3 Generic Examples Evaluated

Three generic examples typical of Canadian uranium tailings impoundments were defined to include a variety of representative containment structures built from materials characteristic of those that have been used in equivalent structures. A detailed description of these structures, the tailings they contain and their environmental setting is provided in Technical Memorandum (TM) II.

The generic sites should not be considered to be entirely representative of any existing or future tailings deposit. They serve to evaluate the methodology and results of long term stability analyses, using representative conditions, and do not necessarily reflect the conditions at any existing site. Existing impoundments differ in their details of site layout and characteristics, and their final reclamation and abandonment preparation may differ entirely from any of the alternatives evaluated herein.

(i) Ontario Site

The generic tailings site for Elliot Lake has been placed in an existing steep walled, rock rimmed, lake basin shown in Figure 3. Characteristics of the various components of the impoundment have generally been drawn from the Quirke basin. However, as many of these components are similar to the other impoundments in the area, certain generalizations have been made in



SITE PLAN

STRUCTURE LAKE TAILINGS MANAGEMENT AREA
GENERIC ELLIOT LAKE SITE

Legend

--- Diversion Channel

Discharge Location

Spillway

Treatment Plant

Dam

0.5% Direction & Degree of Surface Slope

Scale 1:25,000
Contour Interval - 50'
Contours In Feet A.S.L.

FIGURE 3

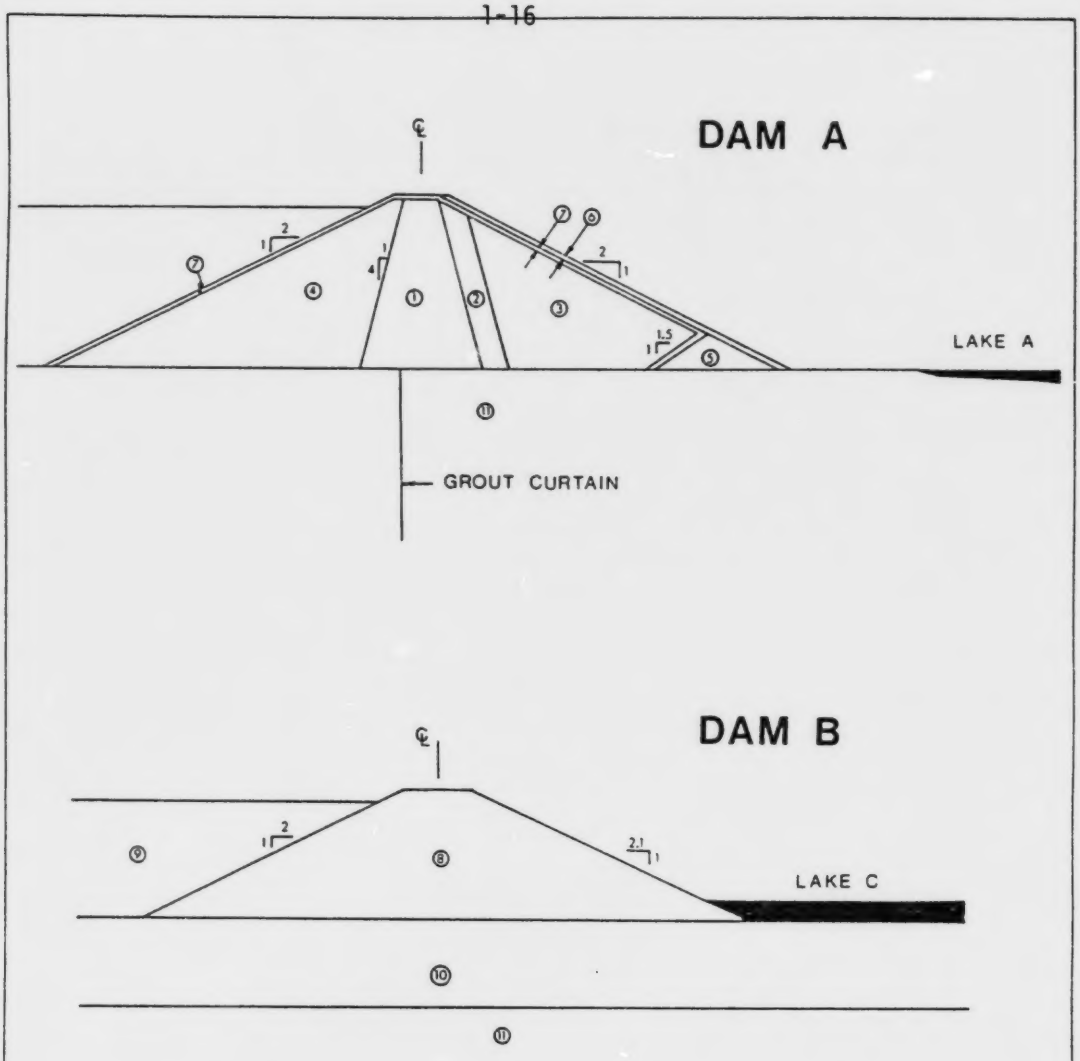
order to better represent a site typical of the Elliot Lake area. The impoundment covers 160 hectares and contains approximately 35 million tonnes of tailings. Two dams, A and B are situated at the northerly and southerly ends of the impoundment. Typical cross-sections for these dams are shown on Figure 4.

(ii) Saskatchewan Sites

Because of the variation in the ore types as well as the tailings placement methods used in Saskatchewan, two generic sites have been selected.

A generic wet tailings site has been defined which contains many of the characteristics typical of the tailings deposits associated with the lower grade Saskatchewan ore deposits. These tailings have low nickel and arsenic contents, and have been placed by mass discharge behind embankments of more traditional design. The layout of this impoundment is shown in Figure 5 and a typical embankment cross-section in Figure 6.

A generic semi-dry tailings site has been defined which is more representative of the managed layered tailings deposit being formed at Key Lake. The tailings are derived from higher grade ore deposits and contain considerably greater fractions of radiological waste products as well as other toxic elements such as nickel and arsenic. The layout of this impoundment is shown in Figure 7 and a typical embankment cross-section in Figure 8.



TYPICAL CROSS SECTION
DAMS A & B

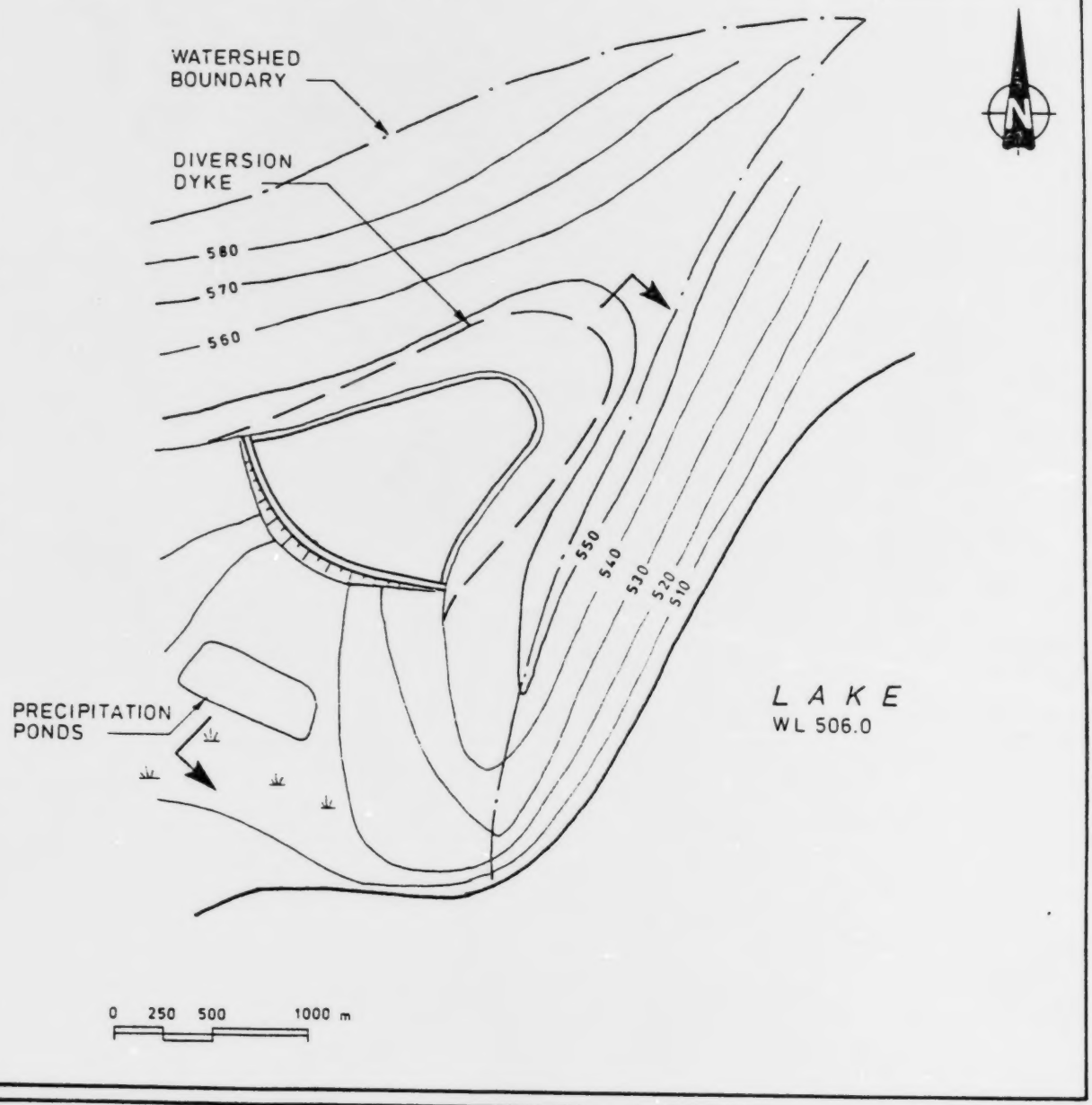
(GENERIC ELLIOT LAKE SITE)

Legend

① CORE-GLACIAL TILL
② FILTER-PROCESSED SAND
③ DOWNSTREAM SHELL-SAND AND GRAVEL
④ UPSTREAM SHELL-TAILINGS SAND
⑤ DRAIN-PROCESSED GRAVEL
⑥ EROSION PROTECTION-COBBLES
⑦ BEDDING/EROSION PROTECTION-SELECT SAND AND GRAVEL
⑧ WASTE ROCK
⑨ TAILINGS
⑩ OVERBURDEN/GLACIOFLUVIAL SAND AND GRAVEL
⑪ BEDROCK

0 10 20
m

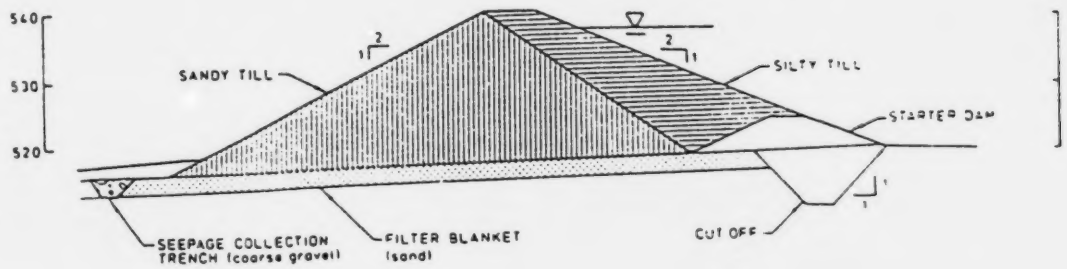
FIGURE 4



SITE PLAN

W.T. (WET TAILINGS) SITE LAYOUT
(SASKATCHEWAN GENERIC WET TAILINGS SITE)

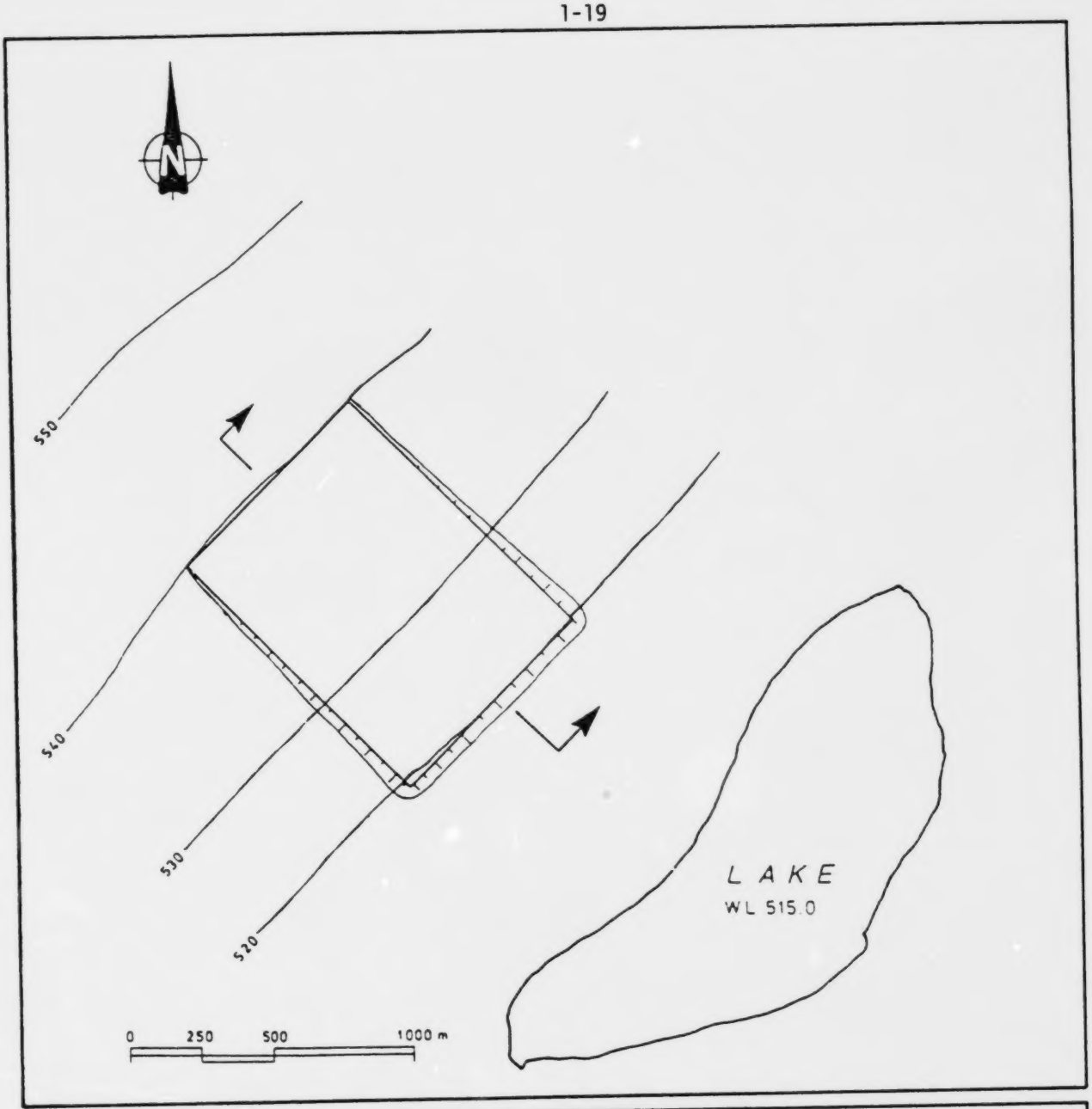
FIGURE 5



W.T. TAILINGS DAM CROSS SECTION

(SASKATCHEWAN GENERIC WET TAILINGS SITE)

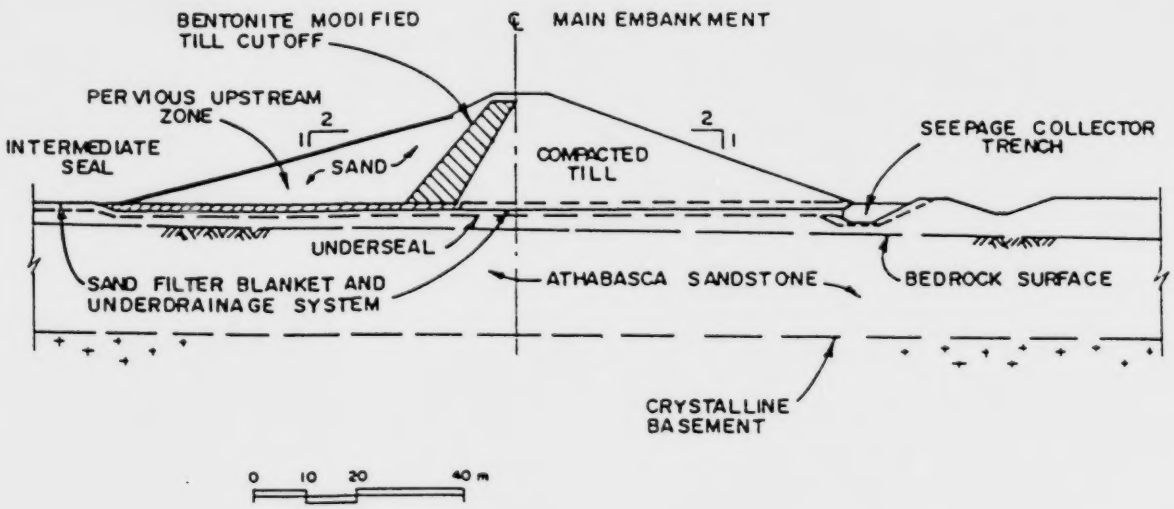
FIGURE 6



SITE PLAN

S.D.(SEMIDRY) TAILINGS SITE LAYOUT
(SASKATCHEWAN GENERIC SEMI-DRY SITE)

FIGURE 7



S.D. SITE, MAIN EMBANKMENT CROSS-SECTION
(SASKATCHEWAN GENERIC SEMI-DRY SITE)

FIGURE 8

2.0 COVER STABILITY AND DESIGN METHODOLOGY

2.1 SHORT AND LONG TERM DISRUPTIVE EFFECTS

2.1.1 Introduction

Retaining structures failure can occur as a result of:

- o large short term forces such as floods, forest fires, earthquakes and extreme frost conditions. Such extreme events happen with a frequency which is generally inversely proportional to the severity of the event.

- o long term degradation which results in a significant change of the original design or design conditions. Examples are sheet erosion, clogging of drainage layers by salt precipitation or roots, weathering and breakdown of riprap armour and salt migration.

Failure of structures will most probably occur as a result of a combination of short and long term effects. For example, salt migration precipitation in drains may result in drain blockage in the embankment causing a rise in the phreatic surface resulting in piping failure of the toe of the embankment followed by general slope failure.

Both short and long term disruptive effects are considered in this section. The recurrence periods or probability of occurrence of extreme events has been evaluated in section IV.2 of Technical Memorandum IV.

2.1.2 Climatic Change

Because of the long period of interest, the likelihood of extreme events occurring is proportionately large. The probability of occurrence of fires, floods, tornadoes or other extreme events, for which there is a record of smaller events, can be determined based on the probability frequency relationships that can be developed for the historical record of events. In Canada, this record is relatively short, generally not more than a few tens of years, and the extrapolation to events that have a probability of occurrence in the very long term of 1000 to 2000 years may be of questionable accuracy. Nevertheless, the methodology is relatively well defined and as the period of record increases, so will our ability to more accurately determine the probability of occurrence of extreme events.

The period of record applies to a period in which a particular climate applied. However, the earth's climate is not fixed. Evidence suggests (McInnis, 1985) that climatic cycles occur regularly, varying from relatively minor 30 year cycles to major glacial and interglacial cycles of tens to hundreds of thousands of years.

The weather of Canada in several years, or its climate a few centuries from now is unknown (Hare and Thomas, 1974). Thus the record from which the projections of extreme events are made may not be representative of the climatic conditions which may cause them over the next 1000 to 2000 years.

While it is questionable whether man has altered world climate to date, the potential for material alteration increases and his influence may rival or overrule natural climatic changes early in the twenty-first century or sooner (Hare and Thomas, 1974).

Substantial climatic changes can cause extreme events of which there is no recent record in the Canadian uranium tailings areas, such as glaciation, extreme drought or high precipitation periods. Even relatively small changes, such as a temperature change of 2 to 3°C, could have large consequences, such as the potential for permafrost and frost heave.

Much of the work summarized in this section is taken from McInnis, (1985) in which a literature review of long term natural events was undertaken for NUTP.

Glaciation

Some general characteristics of climate in the past suggest that an ice age is due (Kilborn and Beak, 1979). The probability of a transition in the next 100 years to the type of climate leading to an ice age is quoted by Pittock et al, (1978) as being less than one percent. The probability of onset within the next 1000 years of glacial climate associated with the 100,000 year glacial-interglacial cycle is estimated by Lamb, (1977) to be about two percent.

Greenhouse Effect

Two models (Bruce and Hengeveld, 1985 and Parry and Carter, 1984) predict some effects in Canada of the increased carbon dioxide in the atmosphere resulting from man's activities. They conclude that the temperature rise will be about 2.5°C and 2.5° to 5°C for the Saskatchewan and Ontario tailings site areas, respectively. Natural vegetation of northern Saskatchewan will change from moist boreal forest to cool temperature steppe while that at Elliot Lake will remain cool temperature forest. Since recorded data of the past century indicate that so far, no temperature rise due to carbon dioxide has occurred (Hare, 1981 and Ellsaesser, 1985), predictions should be treated with skepticism.

Climatic Cycles

Associated with the short duration climatic cycles there will be periods, for example, which are both wetter and dryer than that measured in the period of record. Shorter periods (of a few years) which are significantly wetter (wet periods) or dryer (droughts) will occur. These periods will have a major impact on such aspects as vegetational survival and the height of the phreatic surface in the tailings impoundments. Average temperature variations can be expected to result in periods of aggradation and degradation of frost, a major potential disruptive force in Canada. Since one is unable to predict such changes they can only be allowed for in a subjective or parametric way in the long term stability evaluations.

2.1.3 High Precipitation

The methodology for flood estimation has been presented in Section III.2.1 of TM III.

Estimates of the high precipitation events up to the 100 year 24 hour storm event for the Elliot Lake and Uranium City (Saskatchewan) areas are given in Tables I.2.A-2 and I.2.B-4. There is a maximum flood of which the catchment basin is capable, termed the probable maximum flood (PMF), which is associated with the probable maximum precipitation event (PMP). The PMP for the Elliot Lake area has been estimated at 420 mm in a 12 hour period (Pullen and Davis, 1981, and MacLaren and Golder, 1980) and about 300 mm in northern Saskatchewan (see section I.2.2.B). These probable maximum precipitation events are approximately three times greater than the 100 year 24 hour precipitation events.

2.1.4 High Winds

Tornadoes, tropical cyclones and low pressure storm systems are sources of high winds.

Tornadoes

Tornadoes do not occur in northern Saskatchewan. Elliot Lake lies in the zone of average annual tornado frequency of 0.4 to 0.8/10,000 km^2, (Newark, 1983). This demonstrates that the Elliot Lake area will be struck by several tornadoes in the 20 to 2000 year period. Though they are the most destructive of all winds, their duration at a site is too short to weaken an impoundment (Kolousek, 1984).

Tropical Cyclones

There is no record of tropical cyclones in northern Saskatchewan.

Out of 350 Atlantic tropical cyclones during a fifty year period only 25 had noticeable effects on weather in southern Ontario, and only eight caused high winds or excessive rain.

The hurricane return period at Elliot Lake is estimated at 100-200 years (Newark, 1985).

Low Pressure Systems

At the Saskatchewan and Ontario sites, damage to tailings impoundments from high winds is normally due to the low pressure storm systems that are a regular part of the weather (McInnis, 1985). In comparison, tropical cyclones pose a small threat.

Low pressure storm systems are most intense in winter. Peak gusts from thunderstorms in both tailings areas lie between 70 and 90 km/h (19.2 and 25 m/s) (McInnis, 1985).

2.1.5 Earthquakes

Dynamic loads due to earthquakes may result in the liquifaction of low density saturated tailings or uncompacted saturated portions of granular embankments or embankment foundation materials.

The Saskatchewan sites are located in a zone of relative seismic stability with a low potential for seismic accelerations at a level likely to induce slope instability or liquifaction.

In the Elliot Lake area seismic activity is low but not negligible. The "Maximum Credible Earthquake" likely to effect the area is of magnitude 6.5 on the Richter Scale (Reades et al, 1982) and is located 230 km from Elliot Lake. It is predicted that the event would cause an intensity IV effect, on the Modified Mercalli Scale, at Elliot Lake, with corresponding peak ground accelerations of 0.065g. Studies by Golder Associates, 1982, and Weston Geophysical Research Inc., 1979, on the potential of liquifaction of tailings indicate that the potential is low, and that the embankments studied would be stable.

Mining induced seismic events have been occurring in the Elliot Lake area as a result of pillar bursting and mine collapse (Hedley et al, 1984). Some of these events have exceeded magnitude 3.5 on the Richter scale. Because of the close proximity of these events, the potential exists that mining induced seismicity would possibly influence impoundment stability.

2.1.6 Forest Fires

All the uranium tailings areas are within natural forest cover areas which have been swept with forest fires at irregular intervals. Past experience is that forest fires are followed by rapid re-generation of the vegetation covers. The greatest risk associated with the temporary loss of cover is the potential for erosion, upward salt migration and frost heaving. Since forest fires may be anticipated on several, if not numerous, occasions in the 100 to 2000 year period of interest, the secondary effects may be severe.

2.2 ESTABLISHMENT AND LOSS OF VEGETATION COVER

Vegetation cover is reviewed here because it is considered to play a primary role in the long term stabilization of both covers and containment structures in Canada.

Vegetation may be used as the primary stabilizing agent for surface drainages and ditches (diversion structures). The drainages may be installed at the time of reclamation or may develop naturally as a result of long term gully erosion.

Vegetation growth within such drainages or diversion structures may also be responsible for channel blockage and root action may effect the integrity of subsurface drainage layers.

Stabilization of surface covers is required (by either vegetation or a riprap cover) to prevent erosion with subsequent sedimentation and blockage of surface drainage ditches or diversion structures.

2.2.1 Object and Methods

Forest is the climax vegetation cover for both the Elliot Lake and northern Saskatchewan uranium mining regions of Canada. Climax vegetation cover represents a comparatively stable and long-term form of cover for a region. Long-term change in the nature of a climax cover is determined by global changes in environment only, (e.g., cooling or warming of the earth's atmosphere, glaciation, greenhouse effects). Man-induced destructive changes or natural catastrophes, e.g., fire or disease infestation may destroy a climax vegetation cover but they do not prevent the natural re-occurrence of the climax vegetation over time. The nature of the destruction only determines the time rate at which the climax vegetation will be re-established.

A vegetation cover design guide has been prepared for U.S. uranium tailings deposits by Beedlow, 1984. This design guide, while it illustrates and discusses many of the aspects relevant to vegetation cover design is not of direct application to Canadian uranium tailings deposits.

Uranium tailings abandonment procedures in the western United States have not considered the establishment of a forest cover as a final vegetation cover. The climax vegetation cover for the uranium producing areas of the western United States is grassland. The difference between northern Canada and the western United States in determining the form of the climax vegetation is generally due to the reduced level of precipitation in the latter area. Precipitation levels in both the Elliot Lake and northern Saskatchewan regions are not a primary restrictive factor in forest development.

The possibility of a forest cover considerably increases the advantages and potential for vegetation cover as a primary cover type in Canada. Greater emphasis should be given to this cover form in developing long term stable covers than is given to it in the U.S.A.

The technology of direct vegetation for Canadian conditions is reviewed in sections III.2.7 and IV.1.2 of the Technical Memoranda.

2.2.2 Loss of Vegetation Cover

The most common causes of loss or failure of a vegetation cover on tailings or embankment surfaces is inadequate site preparation. That may take many forms:

i) Failure to adequately design final surfaces to prevent erosion, persistent ponding, water, or compaction of overburden covers during placement.

ii) Insufficient addition of soil amendments to counteract tailings acidity or alkalinity (salinity).

iii) Acid seepage (particularly in the toe area of embankments)

iv) Inadequate determination of plant fertilizer requirements.

v) Selection of inappropriate plant species for the initial vegetation cover.

vi) Unsatisfactory seedbed preparation.

vii) Seeding at the wrong time of year.

There are numerous other causes of vegetation loss, some of which can be controlled to a certain degree.

i) Destruction of vegetation by recreational vehicles.

ii) Catastrophic events such as flooding and erosion from severe storms (100 year event) and forest fires.

iii) Insect and/or plant disease epidemics.

(iv) The failure of chemical control procedures over a period of time, i.e., onset of re-oxidation of iron sulphides.

2.2.3 Vegetation Stability at the Generic Sites

It is anticipated that stable forest type cover can be established on all embankments at all the generic sites. The establishment of forest type vegetation on the cover and along diversion structures on the cover is less certain.

Difficulty has been experienced with the establishment of stable direct revegetation of tailings from low/medium grade ores in both Saskatchewan (represented by the generic Wet Tailings Site) and Ontario (refer section V.1.2). Because of their acid generating potential, sulphide tailings (typical of Elliot Lake) pose a potentially greater problem. The placement of a pyrite free tailings layer on top of the pyrite tailings (refer section V.1.2.1.1) should enable revegetation leading to a forest climax to be achieved. Research is needed to establish what upward migration of salts will occur. Current field observations in Elliot Lake (Denison, personal communications) suggests that with the excess precipitation in the region there is little or no upward salt migration.

Acid seepage in the toe area of the embankments for both the generic Elliot Lake site and Saskatchewan semi-dry site could occur. This is expected to lead to local forest cover kill. The areas effected by such seepage are likely to be small and acid tolerant vegetation species are expected to develop.

Tree cover vegetation could be established on a thin soil cover (600 mm) but the stability of this vegetation will depend on preventing upward migration of salts and acidity.

Should the tailings from the nickel/arsenic ores (represented by the Semi-Dry tailings site) be phytotoxic then forest vegetation may be impossible on thin covers and thick covers would have to be employed.

Provided appropriate cover construction and placement techniques are used, forest type covers could be established on thick covers on all tailings types. Adequate precautions are needed to prevent salt migration, flooding, etc.

2.3 WATER EROSION

Water erosion is one of the more likely mechanisms of long term disruption of containment structures. Mechanisms of interest include:

2.3.1 Flood Erosion

A substantial proportion of total erosion occurs during extreme precipitation and flood events. The methodology for flood estimation is reviewed in section III.2.1 of TM III, and the determination of river erosion potential and its impacts on tailings impoundments in III.2.2.

None of the generic sites are located in areas threatened by river flood erosion.

The erosion of drainage channels, spillways and diversion structures, during flood events, is reviewed in section IV.5.2 where design methodologies are identified.

The probability of failure due to flooding will depend on the design criterion used to design the structure, and the degree of scour, sedimentation and/or blockage which has occurred.

The majority of the diversion and spillway structures at both the Ontario and Saskatchewan sites are designed for the one in one hundred or one in two hundred year flood events. Thus the design flow is expected to be exceeded several times in the period of concern. This form of failure is considered almost certain to occur unless larger events are designed for during reclamation. Table 2 indicates the probability of occurrence of events with particular return periods within a given time interval. For example, there is a probability of 63% and 18% of the 1000 year flood or 5000 year flood respectively, occurring within the next 1000 years.

It is the authors recommendation that all water storage, drainage and diversion systems that are required to function in the long term be designed to accommodate the Probable Maximum Flood (PMF).

Where water treatment is required for long term environmental protection, the effects of flood flows through the treatment system storage areas must be considered.

No suitable procedures are available for predicting the likelihood or impact of blockage due to debris and/or ice. With the development of a forest type cover it is anticipated that a considerable amount of forest debris will be produced. Some of the thickest vegetation cover may develop

TABLE 2

PERCENT PROBABILITY OF OCCURRENCE OF EXTREME EVENTS WITHIN SELECTED TIME INTERVALS
(Schumm et al, 1982)

Event Return Period (years)	Selected Time Period 1	10	100	1000	5000	10000
500	0.2	2	18	86.5	99.995	99.999
1000	0.1	1	9.5	63	99.33	99.99
5000	0.02	0.2	2	18	63	86.5

Explanation: There is an 86.5 percent probability that a flood event, exceeding in size the 1 in 5000 year flood event, will occur within the next 10,000 years. There is a 2 percent probability of such a flood occurring within the next 100 years.

in and adjacent to the diversion structures. Sedimentation is expected in the flatter portions of diversions as well as behind any blockages that occur. It is anticipated that, in the absence of maintenance of the diversion structures, blockages due to sedimentation and debris will be a regular occurrence. Ice formation and iceflows may also produce blockages in drainage ways, particularly during spring.

Once a blockage occurs the following consequential failure can result:

- flooding of a portion of the impoundment cover resulting in a killing off of vegetation cover and increased infiltration

- flow outside of the designed, erosion protected flow channel. This may result in rapid scour of the adjacent terrain and failure of the diversion structure. This will in turn result in additional scour and general erosion.

Erosion, as a consequence of diversion structure failure following diversion structure blockage by debris, sediment or ice, is considered to be a potential cause of major uranium tailings releases. Since this failure mode is one of successive erosion, releases can be kept small by periodic maintenance.

The potential for diversion structure failure at each of the generic tailings sites is evaluated in section V.3.2 of Technical Memorandum V. It is concluded that diversion and spillway failure is anticipated at each of the sites as currently designed. The amount of channel erosion that would occur with such failure was estimated for the Saskatchewan Wet Tailings (W.T.) site, using the WASHED model (refer section III.2.3) at up to 0.2 m for the 2 year event and over 1 m for the 100 year event. These rates of release of tailings would be unacceptably large.

Appropriate control structure design to prevent such large releases would involve:

(i) Design and construction of diversion structures to accommodate the PMF with ample width and size to allow for partial blockage or sedimentation.

(ii) Use of heavy riprap (or waste rock) armouring along flow channels and on adjacent slopes that may be flooded should blockage occur. Methods for erosion protection design are given in section III.2.5 and 6, and examples of designs for large flood events in Walters and Skaggs, (1984).

2.3.2 Sheet and Rill Erosion

The available technology for the estimation of sheet and rill erosion is reviewed in section III.2.3. Methods for the design of erosion resistant covers are described in III.2.5, discussed and evaluated in IV.4.1 and applied to the generic sites and embankments in V.2.1.

The most suitable methods for predicting sheet and rill erosion are:

a) Unified Soil Loss Equation (USLE) (Wischmeier and Smith, 1978)

b) Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975)

The USLE estimates gross soil losses for all water erosion from an area. The MUSLE can be used to determine soil loss from single storm events which can be large for large storm events. Estimates of soil loss are based on a number of factors which have been developed for various regions of the U.S.A. These factors are not necessarily representative of Canadian conditions but must be used in the absence of any factors developed specifically for Canada. It is recommended that factors appropriate to Canadian conditions be developed to more realistically determine long term erosion potential at the location of the tailings sites.

Computer codes such as WASHMO and WASHED (Ward et al, 1981) can be used for MUSLE calculations.

Using these methods, the erosion release rates over a 1000 year period were estimated for each of the generic tailings sites and the results are summarized in Table 3.

From the tabulated results the following conclusions can be drawn:

- Bare soil would result in excessive sheet and rill erosion of the embankments for Dam A at the Elliot Lake site and at the S.D. site in Saskatchewan.

- Only moderate losses occur with bare tills at the W.T. site and losses are very low for Dam B. This shows the effect of gravels in the embankment soils.

- Good grass cover does much to control this form of erosion which becomes insignificant with forest cover.

- The cobble riprap proposed for Dam A is an effective erosion control layer.

From this evaluation it is apparent that sheet and rill erosion of the embankments is expected to not cause significant erosion and instability of vegetated or riprap covered slopes. Only in the case of the S.D. site with its highly erodible embankment material is significant sheet erosion anticipated over 1000 years.

2.3.3 Gully Erosion

The only method of gully erosion estimation which may be applicable to stability analyses for embankments is the method proposed by Falk et al, (1985). The method of gully erosion prediction is described in III.2.4 and its application to Canadian conditions evaluated in IV.3.1. Limitations of this method are:

- developed from limited American data
- not developed for uranium tailings data

TABLE 3

ESTIMATED SHEET AND RILL EROSION FOR EMBANKMENTS
AT GENERIC CANADIAN TAILINGS SITES
OVER A 1000 YEAR PERIOD

COVER TYPE	EROSION DETERMINED BY USLE* (m)	EROSION DETERMINED BY MUSLE** (m)	TOTAL EROSION (m)
A. Elliot Lake Site			
(i) Dam A			
(a) bare soil	10	1.5	11
(b) good grass	1	0.15	1.1
(c) forest	<0.2	0.03	<0.2
(d) riprap	insignificant	insignificant	insignificant
(ii) Dam B			
(a) bare soil	0.6	insignificant	0.6
(b) good grass	insignificant	insignificant	insignificant
(c) forest	insignificant	insignificant	insignificant
B. Saskatchewan			
(i) Wet Tailings Site			
(a) bare soil	1.0	1.6	2.6
(b) good grass	<0.2	<0.2	<0.4
(c) forest	insignificant	insignificant	insignificant
(ii) Semi-Dry Tailings Site			
(a) bare soil	10	40	very large
(b) good grass	1	4	5
(c) forest	<0.1	0.4	<0.5

Factors used for erosion estimation are given in TM V - V.2.1.

- does not account for variations in vegetation cover
- is based on data from impoundments less than 35 years old and is considered invalid for periods greater than 200 years

Using this method the depth of gully incision was estimated (Refer TM V.2.1) for the embankments at the various generic impoundments as summarized in Table 4.

Since the period under consideration is only 200 years, it is apparent that gully erosion can be anticipated to be a major mechanism of embankment failure. Even if some allowance is made for erosion protection from vegetative cover, failure due to gullying is expected to occur within a few hundred years in embankments constructed of erosion susceptible materials and at a 2:1 slope such as at the S.D. site.

The stabilizing effect of riprap protection is clearly demonstrated by the insignificant erosion on the slopes of the cobble riprap protected Dam A at Elliot Lake.

Because of the small size (D_{50}=10 mm) and uniform grading of the rock waste used for Dam B it is still susceptible to gully erosion. This highlights the need for well graded and coarse riprap materials.

In making the above estimates of depth of gully erosion it was assumed that no water will drain from the cover over the embankment crest. This assumption is made to limit the drainage tributary area and hence the depth of gullying. If the effective drainage area was increased by drainage from the cover then the depth of gully erosion would increase greatly. This highlights the need to ensure that long term drainage on the surface of the impoundment should be away from the embankments and towards a secure erosion resistant spillway discharge channel.

2.4 WIND EROSION

Wind erosion could be a major release mechanism where embankments are unprotected by either vegetation or riprap cover.

The methods of determining wind erosion and release rates are reviewed in section III.3.2 to 3. The application of this technology to Canadian tailings deposits is reviewed in IV.3.2 and estimates of release rates are made for the three generic sites in V.2.2. The results of these estimates are summarized in Table 5.

The analysis does not allow for the long term effect of coarse particle accumulation that occurs during wind deflation. This effect is expected to be very significant where the tills contain significant percentages of coarse particles. Since most of the tills at the generic sites contain a significant proportion of gravel sized particles (refer Figures II.3.4-2 and 3, and II.4.4-1), the amount of deflation required to produce an armoured surface can be quite small (a few tens of centimeters). The selection of tills with high gravel contents would be an effective wind erosion protection cover.

TABLE 4

ESTIMATED DEPTH OF GULLY EROSION ON
EMBANKMENTS FOR GENERIC IMPOUNDMENT SITES
FOR A 200 YEAR PERIOD

SITE	EMBANKMENT	GULLY INCISION DEPTH (m)
1. Elliot Lake Site	Dam A (with cobbles)	negligible
	Dam B	2.5
2. Saskatchewan Wet Tailings Embankment		1.5*
3. Saskatchewan Semi-dry Tailings Embankment		15*

*Assumes 2:1 embankment slopes

TABLE 5

SUMMARY OF WIND EROSION RELEASE RATE
ESTIMATES FOR VARIOUS EMBANKMENT MATERIALS
AT GENERIC CANADIAN TAILINGS SITES OVER 1000 YEARS

SITE	WIND EROSION DEPTH (m)
1. Elliot Lake Site	
Dam A, cobbles & gravel (80% non-erodible) & grass cover	negligible
Dam B, rock waste (70% non-erodible) & grass cover	0.2 - 0.4*
2. Saskatchewan Wet Tailings Site	
Sandy till, (40% non-erodible) & grass cover	2 - 6 m*
3. Saskatchewan Semi-Dry Tailings Site	
Silty till, (30% non-erodible) & grass cover	3 - 12 m*

*With forest cover, wind erosion will reduce to a small fraction of this amount.

Based on the results in Table 5 and the above observations it is concluded that:

- o unacceptably high wind erosion rates occur on silty or sandy soil embankments (without gravel) unless a tree cover is established. Loss of tree cover (due to forest fires) could result in unacceptably high rates of wind erosion releases from such embankments.

- o till, with a substantial gravel percentage, and rock waste will form effective wind erosion layers when placed in thin (600 mm) cover layers.

- o embankments constructed of till or with till covers and forest cover are expected to be stable against wind erosion in the long term.

2.5 FROST ACTION

Frost action can deteriorate water retaining embankment structures. Firstly, repeated freezing and thawing can develop a cracked structure in the embankment, increasing its permeability. Secondly, if the embankment is frost susceptible, moisture can accumulate upon freezing and, upon subsequent thaw, develop excess pore water pressures in the embankment which reduce the slope stability.

In addition to the above mechanisms of embankment deterioration, frost penetration may result in the freezing of drains or drainage layers near the face of the embankment. With drainage blocked by freezing, a build up of pore pressures may occur in the toe area of the embankment resulting in failure or slumping of the embankment.

Frost action requires 3 essential elements.

a) freezing temperatures
b) a frost susceptible soil
c) a free supply of water

The Saskatchewan uranium producing areas are in northern latitudes where severe winters are common. The conditions are sufficiently severe for discontinuous permafrost to occur which becomes more prevalent in the more northerly latitudes. Although the Ontario uranium producing areas are more moderate in climate, (permafrost has not been encountered in the tailings) freezing conditions are common. The approximate freezing indices are 3200, 2700 and 1100 degree days Celsius at Uranium City, Key Lake and Elliot Lake, respectively.

The tailings are predominantly composed of silt and very fine sand sized particles and are frost susceptible. The uranium producing areas are all north of the sedimentary basin. Thus, fine grained clay soil is not available for embankment construction and frost susceptible silt or silty sand is the least permeable soil available. Therefore, both the tailings themselves and the borrow soil available for embankment and cover construction are generally frost susceptible.

The methodology for the estimation of frost depths and aggradation is reviewed in section III.4.1 and 2. This methodology has been applied to typical conditions for northern Saskatchewan tailings sites and for various cover materials in section IV.3.5.3. The resulting estimates of freezing and thawing depths are given on Figure 9. The area above the diagonal line illustrates conditions favourable for permafrost formation while areas below the line illustrate conditions unfavourable to permafrost formation. In most of the cases analyzed, the seasonal depth of frost was greater than the seasonal depth of thaw, which would result in the development of perennially frozen soil.

Frost penetration is dependent upon the thermal characteristics of the cover material, moisture content, height of the water table and vegetation cover. The effect of vegetation cover and depth to water table on the segregational heave is illustrated for the Saskatchewan wet tailings site in Figure 10.

Permafrost development and the associated frost heave may effect drainage facilities or control structures located on the surface of the impoundment. The potential for surface heave is considered more fully in Steffen, Robertson and Kirsten, 1986.

Freeze thaw calculations were carried out on the embankment soils (IV.4.5). The depth of frost is 2.5 m and depth of thaw is 3 m for a sandy embankment with a moisture content of 10%. Thus permafrost aggradation in the embankment soils evaluated is not favoured. The effects of slope exposure which would favour freezing on north facing exposures was not considered.

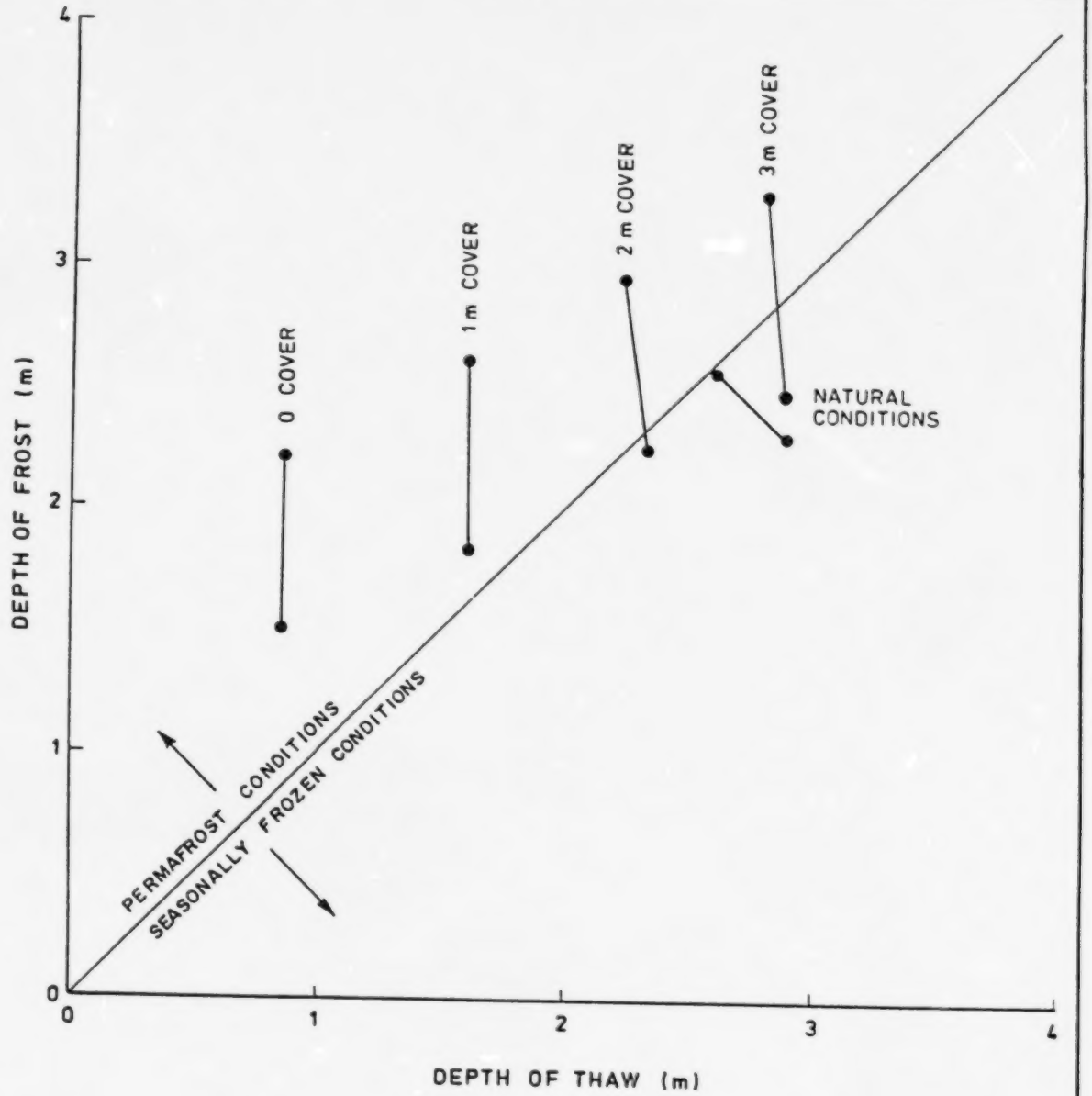
The silty till is frost susceptible. However, because of the permeability characteristics, it can be expected to drain quite rapidly upon thaw and significant excess pore pressures are not anticipated. Freeze thaw behaviour is illustrated somewhat by the natural slopes. In general, stable slopes exist at a slope of 3:1. If significant excess pressures developed, the slopes would have slumped through time to a much shallower slope. Some slopes of 6:1 have, however, been observed. As the silt content increases the effect of frost will become a greater factor in overall instability. In pure silt embankments, Solymarr and Nunn (1983) reported significant embankment distress from frost action.

Evaluations of frost action at the two generic Saskatchewan impoundment sites are described in V.2.4. The following conclusions are reached:

- With side slopes of 2:1 the slopes are marginally steeper than some natural slopes in the area. Allowing for variations in slope exposure and annual severity of frost, it is anticipated that frost induced slumping will occur.

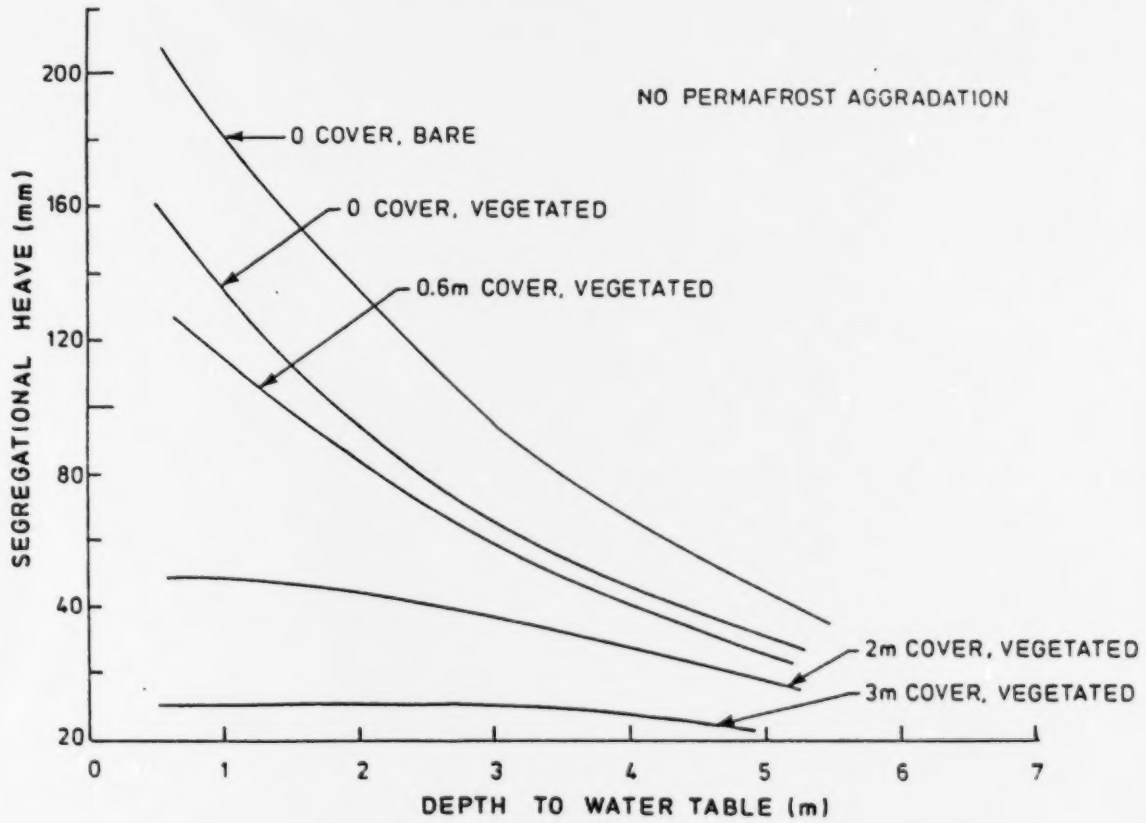
- Vegetation cover considerably reduces frost action. With such cover, embankments constructed with 3:1 downstream slopes may be stable against frost slumping in the long term.

- The 6:1 slope evaluated as a close-out slope is more than sufficient for protection against slumping in these materials, and, with appropriate evaluations, could be steepened.



COMPARISON OF FREEZING AND THAWING DEPTHS FOR TYPICAL NORTHERN SASKATCHEWAN CONDITIONS

FIGURE 9



POTENTIAL TAILINGS FROST HEAVE, W.T. SITE
NORTHERN SASKATCHEWAN

FIGURE 10

- Where bentonite modified clay cores are used (as at the S.D. site), this may be susceptible to frost action depending on the percentage of bentonite used.

With a frost penetration depth of 2.5 m to 3 m in severe winters, freezing of the downstream face and drain outlets is anticipated. Unless the drainage discharges are protected by adequate cover, this is a likely cause of pore pressure buildup in the underdrainage system in the area of the toe of the embankment, and of subsequent slumping. Flattening of the slope to 6:1 would provide ample cover, but other methods of providing cover or ensuring drainage may be more economical.

2.6 BIOLOGICAL PENETRATION

2.6.1 Root Penetration

In general root action is considered to have an overall beneficial effect on embankment and other structures in providing a binding effect and resisting soil erosion. Two possible destabilizing effects have been observed:

(i) Roots may penetrate through low permeability covers and, on decomposing, provide preferential seepage channels which could result in piping.

(ii) Extensive root development in moist permeable drains or drainage layers may ultimately result in clogging of the drainage system.

The factors effecting root penetration through low permeability layers and drains have been reviewed on sections III.5.1 and IV.3.3. Its effect on embankments is considered in IV.4.3.

Since the tailings impoundments contain tailings of relatively low permeability, the risk of piping failure following root penetration through the embankment core is not considered to be a significant potential failure mode.

It is considered likely that with forest development on and adjacent to embankments that roots will seek out and invade any unflooded drainage layers in which the seepage water is not phytotoxic. The likelihood of drain and drainage layer blockage is therefore significant. This would result in increased pore pressures in the toe region of the tailings impoundment with the potential of increased piping failures or slumping in this region.

All the embankments at the generic sites (except Dam B) contain internal drains or drainage layers, which could be come plugged.

The current understanding of the potential of biological penetration by root action was insufficient to enable release rate estimates to be made within the scope of this study. However, the potential of increased releases by this mechanism is considered to be relatively minor.

Methods to reduce the potential for drain blockage are:

(i) Ensure that drains in potential root zones operate in a flooded condition.

(ii) Use large drains with surplus drainage void space.

Vegetation growth and blockage of surface drainage ditches in the long term is considered to be almost a certainty. Consequential releases have been estimated in section 2.3.1.

2.6.2 Burrowing Intrusion

The potential for burrowing intrusion has been reviewed in III.5.2. Because of the large size of the embankment structures, the extent of burrowing required to effect stability is large. Concern regarding the effects of burrowing animals has been expressed for U.S. uranium tailings impoundments. Because of inherent differences in climate, vegetation type and accompanying differences in biota type and population, burrowing activities are not considered a significant mechanism for potential instability of Canadian uranium tailings control structures.

It is presumed that the prevention of intrusion by man will be assured by institutional or other means.

2.7 WEATHERING, LEACHING AND PRECIPITATION

2.7.1 Weathering

Embankment materials formed from the soils excavated from the vicinity of the tailings impoundment are expected to be geochemically stable and undergo little change due to weathering in the 1000 to 2000 year period of interest. The same conclusion applies to riprap materials derived from coarse till deposits.

Waste rock from the mine or riprap quarried specially for the embankment may be geochemically less stable and their long term stability should be evaluated. Methodologies for the assessment of the durability of such waste rock/riprap cover materials has been reviewed in section III.2.10.

Durable sandstone and quartzite rock waste and quarry material can be obtained at the generic Saskatchewan and Ontario sites. Thus, weathering of embankment materials is not considered a potential cause of instability and releases for any of the embankments evaluated.

2.7.2 Salt Migration

(a) Leaching

The geochemical processes for the leaching of uranium tailings and solute transfer have been identified in section III.6.7. Geochemical effects and pore water changes have been evaluated and projections made of the change of pore water chemistry with time in IV.3.4. An evolution of pore water

geochemistry at the Elliot Lake site is anticipated, Clifton Associates (1986), as follows:

0-20 years (or impoundment operational life)	-	process controlled stage
20-~200 years	-	sulphide oxidation stage
~150-~600 years	-	resolution stage
~500-~1000 + years	-	long term leaching stage

Data derived for the behaviour of the Elliot Lake tailings reflect periods for tailings deposition and subsequent inactivity of the order of 20 to 30 years. This establishes an approximate beginning for the second stage of pore water evolution. Determining the approximate duration of this stage is problematic. Dubrovsky et al, (1985) note a rate of migration downwards of the acidic zone in pyrite tailings of 0.2-2 m/yr. This rate of downward advance is slower than the infiltration rate/seepage rate, due to the retardation of the acidic zone, through neutralization, during transport downwards. There is a capacity for acid generation until all the pyrite is oxidized, after which the tailings would be "flushed" with relatively low TDS rainfall or snowmelt infiltration. Given the present rate of infiltration, acid generation resulting in a high TDS, high sulphate and iron seepage water composition will continue for many decades.

Based on the above geochemical sequence, an estimate of the pore water quality for various representative Canadian uranium tailings deposits was made as is summarized on Table 6.

The rate of release due to seepage is a function of infiltration and liner permeability. In the long term seepage rates must have a minimum value equal to the infiltration rate. Infiltrating water which does not escape through the liner must emerge as seepage over the rim of the liner.

Infiltration estimates have been made in sections III.5.1, IV.3.6, V.1.5 and V.3.4. Estimates of the infiltration rates for the two generic Saskatchewan sites are summarized on Table 7. Even higher infiltration rates are anticipated at the Elliot Lake generic site due to the higher surface area (160 ha) and higher average annual precipitation (926 mm).

2.7.3 Precipitation and Clogging Potential of Underdrainage

Chemically, the drainage/underdrainage can be considered a transition zone between the pore water composition within the tailings mass and the external environment.

This is because the chemical equilibria or quasi-equilibria that exists in tailings pore water are not necessarily stable in the changed environment of the drain.

The net result of changing equilibria are ex-solution and precipitation reactions. If reactions of this nature persist, there is a potential for

TABLE 6

PORE WATER QUALITY CHANGES WITH TIME

	Process Controlled Stage All Tailings	Sulphide Oxidation Stage Elliot Lake	Resolution Stage ** Elliot Lake Alternative 1	Resolution Stage ** Key Lake and Rabbit Lake Type Alternative 2	Long Term Infiltration Phase All Tailings
pH	7-10	2	3.5	7.5	5
TDS	2,500-8,000	30,000	2,500	2,500	100
Ca	500-800	500	400	400	20
SO_4	1,500-5,000	20,000	1,800	1,200	10
NH_3	<10-350	<10	<10	<10	<1
Na	<50-600	100	20	20	10
Cl	<50-700	200	20	20	10
Fe	<1	10,000.*	20	5	<1
Mg	1-900	200	50	<5	10
As_{226}	.1-2	1	<1	<1	<0.1
Ra^{226}	<20-50	<5	<20	<10	<10
Al	<1-3	20	20	<5	5
Si	<5-20	20	20	<5	5
Ni	<.1-1	1	<.1	<.1-1	<1

pH expressed in standard units; all other parameters in mg/L

* If oxidizing ore is pyrite or iron-bearing sulphide

** May be accompanied by alteration of jarosite, in iron-bearing tailings

TABLE 7

SUMMARY OF ANNUAL AVERAGE INFILTRATION RATES
AND AMOUNTS AT SASKATCHEWAN SITES

	W.T. SITE	S.D. SITE
Precipitation (mm)	400	415
Cover Area (ha)	90	75
Bare Tailings		
Depth of annual infiltration (mm/year)	80	80
Volume of annual infiltration (m^3/year)	72,000	60,000
Waste Rock Cover		
Depth of annual infiltration (mm/year)	160	160
Volume of annual infiltration (m^3/year)	144,000	120,000
Forested Cover		
Depth of annual infiltration (mm/year)	40	40
Volume of annual infiltration (m^3/year)	36,000	30,000
Bentonite Modified Infiltration Barrier		
Depth of annual infiltration (mm/year)	30	30
Volume of annual infiltration (m^3/year)	27,000	22,500

the build-up of precipitate within the intergranular pore spaces of the drainage material or in drainage pipes. Under extreme circumstances, this can result in blockage or clogging of the drain, which consequently can have a negative effect on the stability of the tailings facility.

In general, the chemical species found in tailings pore water that have a "precipitation potential" in a drainage system include:

- o calcium salts - forming carbonate (calcite) or sulphate (gypsum)
- o iron salts - sulphates (jarosite), carbonates (siderite) or hydroxides
- o manganese salts - forming carbonates (rhodochrosite) or oxides (pyrolusite), and
- o silicon - forming silica (quartz)

A. High Sulphide Tailings (Ontario Type)

In the case of the Ontario type of high pyrite tailings, there are two different pore water chemistries, depending on whether oxidation has occurred or not, and hence alternatives for underdrainage blockage potential. Table I.3.A-3 in TM I gives pore water compositions for normal, "neutralized" tailings and oxidized tailings.

In the neutralized case, the analysis indicates that neither calcium nor iron salts are likely to precipitate because:

- o in the case of iron, its actual concentration is not significant (<1 ppm) and any pH change by equilibrating with the atmosphere would cause a lowering of pH and an increase in iron solubility. Hence, precipitation is unlikely; and
- o the combined masses of the cations calcium and ammonium are virtually sufficient to sustain up to 2000 mg/L of sulphate in solution and, hence, gypsum precipitation, if it occurred, would not be large.

The oxidized tailings have a significant potential for iron/iron sulphide precipitation due to the high dissolved concentrations of iron and sulphate combined with pH levels which will not be in equilibrium with the air in or out of the drainage system over most of these ranges. As discussed in section IV.4.4, a small shift in pH value can cause a considerable change in iron solubility.

With iron values between 3,000 mg/L and 15,000 mg/L, (Table I.3.A-3) there is at least the potential for the precipitation of 12,000 mg/L if the pH were to rise from 2 to 6: this appears to be in accord with the general chemistry of ferric iron solubility, in an oxidizing medium, summarized by Hem (1970), and other authors. Expressed as $FeSO_4$ this is equivalent to about 26g of precipitate for each litre of water passing through the drain. Using the 0.12 m^3 void space in a unit length of a 1 m x 0.3 m cross section of an underdrain, described in TM IV, then the void space in the drain could be filled within a matter of days with a flow rate through the

drain of 1 litre per second (32,000 m^3/year). Such calculations assume complete retention of the precipitate in the void space and almost instantaneous reaction.

In practice, the change in pH due to equilibrium with the air will be a slower process, but a pH shift of a unit can result in up to an order of magnitude change in the solubility of iron in some cases. This would still be sufficient to give the potential for drain blockage in a matter of months.

B. High Nickel/Arsenic Sulphide Type (Semi-Dry Tailings Site, Saskatchewan)

In general terms, the potential for drain blockage is low in the S.D. tailings system as compared with the high pyrite, Elliot Lake type of oxidized tailings as pH values are high and the masses of dissolved species in the S.D. pore water are considerably lower for the species liable to give precipitation problems. However, examination of chemical analyses for the tailings effluent discharged to the impoundment from the S.D. mill indicates that, while iron salts precipitation may not be an issue (values for Fe are <0.1 mg/L), there is sufficient sulphate and calcium in solution to make gypsum and/or calcite precipitation a potential problem. (Sulphate and calcium levels from S.D. tailings, Table II.4.3-2, range between 1310-3450 mg/L and 520-1050 mg/L, respectively).

Reduction of the calcium levels from 1000 mg/L to 600 mg/L could be entirely possible, resulting in the precipitation of 400 mg of calcium per litre of discharge in the drain. As calcium sulphate, this is equivalent to between 1360 mg and 1700 mg depending on the degree of hydration of the calcium sulphate (i.e., $CaSO_4$ through $CaSO_4.2H_2O$).

Precipitation of 1.7 g of solids for every litre of water passing through a drain could effect blockage relatively rapidly, if all the precipitate were retained in the drain void space, i.e., within months.

C. Low Sulphide, (Wet Tailings Site, Saskatchewan)

The potential problems associated with drain blockage in the W.T. site appear, at first, to be similar to the S.D. site, due to some similarities in the pore water chemistry of the two types of tailings. The described iron levels are low (0.25 mg/L) and hence the mass of iron precipitate generated would be low, even if there were to be precipitation due to either an increasing pH or Eh.

Sulphate values in the W.T. site are about twice the respective value for the S.D. site at over 6000 mg/L. This high level of sulphate is sustained by the elevated magnesium level in pore water at about 950 mg/L. While there is some potential for calcium sulphate precipitation, the magnesium and sodium in the water would tend to keep most of the sulphate in solution and the total potential for sulphate precipitation is reduced. In essence, it is anticipated that the potential rate and quantity of precipitate for the W.T. site would be less than for the S.D. site.

Appropriate design methods to reduce the potential for drain blockage include:

- o Design the underdrains to remain submerged and flooded to prevent air entry
- o Provide additional void space to accommodate precipitation
- o Limit the rate of infiltration and therefore of seepage to the underdrain system.

2.8 SEEPAGE EROSION

The failure of geotechnical structures due to the flow of water under high seepage gradients is usually described as "piping", "heave", or "internal erosion" failures. The term "seepage erosion" is a general term describing the adverse effects of seepage and includes all of these failure mechanisms. A brief description of each of the mechanisms, their methods of analysis and examples of the circumstances under which they occur, is provided in Table 8.

Methods of analyses for these failures are described in section III.8. Examples of the application of the methods to a typical Canadian embankment structure is provided in section IV.4.7.

These analytical methods were applied to the embankments at the generic uranium tailings sites as described in V.2.6 and the following results and conclusions reached.

A. Elliot Lake Site

(i) Dam A

Seepage erosion failure can only occur if the till core cracks and the filter downstream of the core as well as the toe drains block. This combination is considered highly unlikely.

(ii) Dam B

The tailings have been deposited against the un-zoned waste rock embankment. Hydraulic gradients against the upstream face could approach 1.0. Creep coefficients of near unity are applicable and internal erosion of tailings into the voids in the waste rock can be anticipated in both the short and long term. As the tailings are piped into the waste rock it will become a less effective drain, and mounding of the phreatic surface may occur. In the worst case the waste rock could be completely filled in with tailings and the phreatic surface would be at the surface of the tailings. This "worst case" was evaluated and it was found that the resulting tailings infilled rock waste embankment had a marginal stability against further piping. If a water cover was placed over this tailings dam then there would be a high potential for continued piping and tailings release. If the upper surface was contoured for drainage and a vegetation cover (with or without a soil cap) established then it is anticipated that there

TABLE 8

CHARACTERIZATION OF SEEPAGE EROSION MODES
(Modified after van Zyl and Harr, 1981)

MODE	MECHANISM	METHOD OF ANALYSIS	EXAMPLES WITH RESPECT TO URANIUM TAILINGS IMPOUNDMENTS
Heave	. Simultaneous heaving of substantial soil volume . Shear resistance of soil volume approximately zero	. Comparison of seepage force per unit volume with effective unit weight of selected critical volume of soil	. will occur if gradient increases rapidly . can only occur due to upward flow
Piping	. Initiated locally at discontinuities in the soil, e.g., concentration of fines, particles with low specific gravity or fissures and cracks . Removal of particles begins at soil surface . A space is created at exit which progressively enlarges and works backwards to form irregular channels or "pipes" . Soil adjacent to pipes is stable	. Almost impossible due to control by discontinuities, however, use of "global" gradient (see below) approach is an attempt	. Can occur due to upward flow as well as unconfined flow. Both mechanisms are possible depending on specific conditions.
Internal	. Begins locally by erosion of fine particles being removed from the soil matrix into a coarser layer . Cavities form, leading to collapse and failure	. Attempts have been made to combine effect of particle size distribution and gradient, generally very difficult to analyze. Prevent by using filters criteria	. This mode is considered of lower probability for uranium tailings impoundments

will be a substantial drop in the phreatic surface behind the dam and seepage erosion would not occur.

B. Wet Tailings Site, Saskatchewan

Seepage through the embankment of the W.T. site is controlled by a sloping core. The evaluation of the seepage erosion potential indicated that this could occur only if the following four conditions pertained:

(i) an infiltration barrier is not included in the tailings cover

(ii) the filter drain fails

(iii) the slopes are not flattened from the current slopes of 2:1

(iv) a period of frost aggradation and degradation results in an increase in the permeability of the silty till core.

It is considered unlikely that all four conditions will occur.

Another failure mode which is more likely would result if the exits to the drainage blanket blocked (due to freezing for example). With continued water drainage into the blanket, hydraulic heads would build up in the drainage layer behind the blockage. This would give rise to high seepage gradients along flow paths which bypass the blockage and may result in piping and local failures in the toe region of the slope.

C. Semi-Dry Tailings Site, Saskatchewan

The semi-dry tailings deposit is designed to have a zero hydraulic head at all locations within the tailings mass following decommissioning. To achieve this, the underdrainage system must remain functional. If all components function as designed then there is no potential for seepage erosion type failures. However, should part or all of the drainage system become blocked for any of the reasons listed in section V.2.5, then there is a potential for the water level to mound within the impoundment. Such a mounding would result in a high pressure head on the relatively thin bentonite modified under seal. Seepage gradients conducive to seepage erosion and piping would result.

It is concluded that if underdrain blockage did occur that there would be a high probability of piping and seepage erosion of the underseal.

2.9 PHYSICAL INSTABILITY

2.9.1 Factors Affecting Slope Stability

The stability of a slope is dependent on:

- slope geometry
- engineering properties of the slope materials (shear strength and unit weight)

- pore water pressures in the slope

- dynamic loadings (earthquake loadings)

A sufficient change in any one of these can result in slope instability. The stability of a slope is expressed in terms of a factor of safety (FS) against failure. With FS = 1.0 the slope is marginally stable. Failure occurs for values less than 1.0 and slopes are stable if the factor of safety is greater than 1.0. Slopes are designed to have a reserve of strength which is sufficient to allow for the the uncertainties as well as the long term changes that may occur in the factors which effect stability. Commonly a minimum FS of 1.5 is used for the design of tailings impoundment embankments. Thus embankments, at the time they are constructed, have an ample reserve of strength and instability is unlikely. Before they will become unstable there must be sufficient change in one or a combination of the three factors mentioned above to bring about failure.

The methodology for stability analyses is described in section III.7. An evaluation of the reasons for and ranges of variation of the various factors effecting stability, typical of Canadian conditions, is made in IV.4.6.

2.9.2 Slope Geometry Changes

Slope geometry changes could occur as a result of:

(i) Flood or gully erosion. Magnitudes and rates of flood and gully erosion have been evaluated in section 2.3.

(ii) Freeze-thaw induced slumping as evaluated in section 2.5.

(iii) Seepage erosion as evaluated in section 2.8.

Of these, (i) and (iii) would result in the local steepening of the embankment and may result in slumping of a part of the embankment. Such slumping may effect the discharge of the underdrains as discussed in 2.9.4 below.

2.9.3 Changes in Material Properties

Physical, chemical or biological processes may alter the embankment materials, and their properties, over time. Weathering and strength changes are reviewed in sections III.7.4.2, IV.4.6.3 and 2.7.1.

Little strength change is anticipated in the embankment materials derived from local surficial deposits of sands or tills.

For rock fills, the disintegration due to weathering will reduce the shear strength and the stable angle of repose. For instance, the well graded broken Athabasca Formation sandstone may initially be stable at angles in excess of 38° degrees, but when reduced to sand and gravel sizes by mechanical weathering and leaching, the stable angle can be expected to reduce to about 34 degrees. Similarly, the kaolinized regolith may

initially be stable at a similar angle, but with time will slake to clay with a friction angle of about 25 degrees.

2.9.4 Changes in Pore Water Pressures in the Slope

Pore pressures may increase due to a rise in the water table as a result of:

- Increased infiltration or seepage. This is unlikely since infiltration conditions are generally worst during the operating phase of the impoundment (see section 2.8).

- Increased seepage through the liner or the embankment core due to a number of factors including liner degradation, freeze-thaw failure of the core, leaching or piping of the liner or core.

- Blockage of drains due to:

  (i) piping of fines into the underdrains (see section 2.8)
  (ii) precipitation of salts (section 2.7)
  (iii) root penetration (section 2.6)
  (iv) frost penetration (section 2.5)
  (v) failure of the toe of the embankment and covering of the discharge outlets
  (vi) solifluction or sediment deposition on drain outlets (section 2.3)

The potential for liner failure has been reviewed in IV.5.1 in which it was concluded that:

o Little is known about the long term behaviour of manufactured flexible membranes. In the absence of such information it must be assumed that these membranes will eventually degrade under the influence of chemical, physical or biological attack.

o Uranium tailings leachates will affect the permeability of liners made from natural materials in the uranium mining areas, but the overall effect is expected to be small.

2.9.5 Dynamic Loadings

Dynamic loadings may induce instability as a result of two effects.

(i) increased disturbing forces on the failure surface due to the ground acceleration, and

(ii) increased pore pressures which may result when saturated loose sands or silts compact under the dynamic loads.

These effects are reviewed and analytical methods defined in section III.7.4.5.

The likelihood of seismic events of larger magnitudes occurring at the locations of the uranium tailings deposits in Ontario and Saskatchewan were

defined in section 2.1.5. It was concluded that the risk of events of a size sufficient to cause instability is insignificant in Saskatchewan.

Evaluations of the likelihood of earthquake induced seismicity and the potential for instability at selected impoundments in the Elliot Lake area was investigated by Golder Associates (1982) and Weston Geophysical Research Inc. (1979). They concluded that the potential was low.

It is noted that mining induced seismicity has occurred recently in the Elliot Lake area. The effect of this seismicity on impoundment stability is not known.

2.9.6 Evaluation of Slope Stability at Generic Sites

The factor of safety of all the embankments as built is ample. Provided slopes are not steepened (they remain at 2:1) and they remain well drained, no slope instability will occur.

The greatest risk of slope steepening results from gully erosion. Seepage erosion of the toe area may also become a significant cause of slope steepening.

Significant risk of pore pressure increases due to drain blockage exists due to chemical precipitation, root action, piping in of fines and covering of discharge zones.

A. Elliot Lake Site

(i) Dam A

The potential for gully erosion and slope steepening of this riprap protected embankment is low. Instability due to gully erosion is not anticipated.

The potential for drain clogging due to one or more of the following: chemical precipitation, root activity, frost action and fines migrating into the drains, is considered to be moderate to high. The consequence of this blockage would, however, not be slope instability because of the very high permeability of the rest of the downstream shell. It is anticipated that drain blockage may not result in a substantial rise in the phreatic surface or result in slope instability.

An overall moderate potential of instability in the long term is assessed for Dam A.

(ii) Dam B

While it does not have a drainage layer, Dam B is subject to high seepage rates. The larger void spaces in the waste rock fill will require a larger quantity of infilling before free drainage is inhibited. As there is no filter installed between the tailings and the waste rock embankment it is anticipated that long term internal erosion and piping may transport tailings into the waste rock voids and result in an elevated phreatic

surface. Thus it is again considered that there is a moderate potential of instability in the very long term.

B. Saskatchewan Sites

The embankments at both the Saskatchewan sites are susceptible to gully erosion, and oversteepening, if the slopes are left at a 2:1 slope. The greater erodibility of the S.D. embankment material makes the risk at this site greater.

It is also considered that there is a high likelihood of drain blockage in the long term. The potential for chemical precipitation within the drains of the S.D. impoundment may represent the greatest risk.

It is assessed that the potential of instability due to slope failure in the long term of 2:1 slopes at the W.T. site is moderate to high and at the S.D. site is high.

If the slopes were constructed at 6:1, it is anticipated that they would be amply stable for the expected range of pore water conditions and changes in the shear strength. Potentially, the stability of the impoundment could be reduced if the slopes were steepened by solifluction, surface erosions (gullying), piping or a combination of these factors. Sufficiently extensive erosion to cause failure of a 6:1 slope on which good tree cover has been established is considered to have a very low probability of occurrence.

2.10 PROBABILITY METHODS OF STABILITY EVALUATION

The discussion on physical stability demonstrates that failure, which results in a release of tailings, often occurs as a result of a combination of events, i.e., drains block as a consequence of chemical precipitation causing a rise in the phreatic surface which induces seepage erosion of the toe followed by slumping of the embankment followed by massive gully erosion which extends back into the impoundment.

In order to investigate potential combinations of events, a methodology is required which permits the likelihood of occurrence of chains of events to be determined. Probability methods of hazard analysis provide such a technique.

A probabilistic analysis considers the variability of uncertainty of the parameters which influence an event. The technique is explained in section III.9 of TM III. The end result is an estimate of the probability of occurrence, P, of an event.

The probability of occurrence of a combination of independent events in a complex mode of failure can be evaluated through the use of fault trees and event trees. A fault tree analysis may include a qualitative evaluation of the probabilities of the various faults or failure events leading eventually to the calculation of the probability of the main event (top event). Potential consequences of an initiating event may be be systematically identified with the event tree diagram in which all the possible paths following an initiating event (or top event), each path

leading to a different consequence. Figure 11 illustrates schematic fault and event tree diagrams.

The methodology for the development of fault tree and event tree diagrams is presented and discussed in sections III.9.1 and 2. Examples of its application are given in sections III.9.3 and 4, and in IV.6. These are illustrative examples which serve to illustrate the methodology, and results should not be taken as indicative of estimates applicable to Canadian conditions or any one site.

Figures 12 to 15 show fault trees for failure combinations. Probabilities of the basic failure events can be obtained by using objective or subjective approaches. In order to demonstrate the approach, the fault tree for cover failure will be evaluated. Note that this example is provided as an illustration of the method only. Insufficient work has been done on the definition of the exact conditions applicable to this example to determine realistic values for individual probabilities.

Figure 12 shows the fault tree for cover failure. Table 9 summarizes the subjective probabilities of the basic failure events. Remarks are also included on how to evaluate some of the probabilities more rigorously. The values in Table 9 are based on the assumption that the initial design was adequate.

Following the scheme given in TM III section III.9.1.2, the combined failure probability evaluation can be done as follows:

P [Differential Settlement]

$$= P \text{ [Differential Settlement]} \; P \text{ [Flooding]}$$
$$= (0.001)(0.05) = 5 \times 10^{-5}$$

P [Chemical Attack]

$$= P \text{ [Detrimental Chemical Attack]} \; P \text{ [Flooding]}$$
$$= (0.001)(0.01) = 1 \times 10^{-5}$$

P [Frost Action]

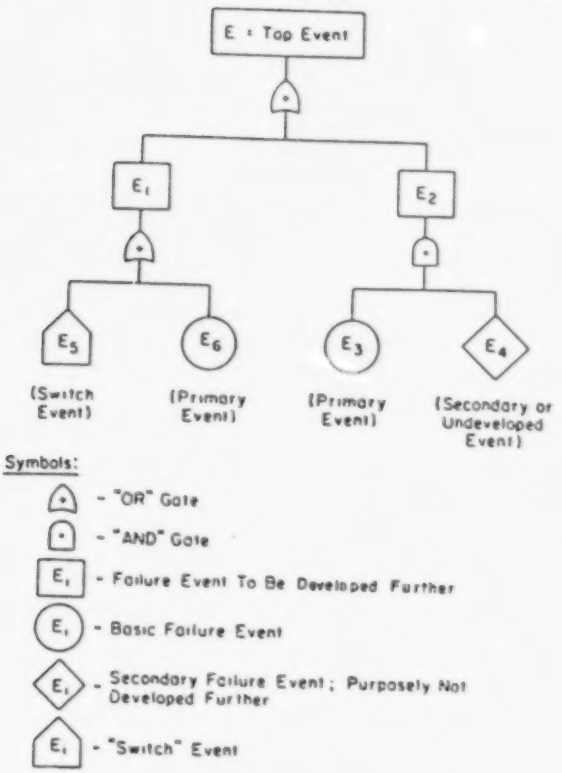
$$= P \text{ [Detrimental Frost Action]} \; P \text{ [Flooding]}$$
$$= (0.001)(0.01) = 1 \times 10^{-5}$$

P [Cover Failure] = P [Differential Settlement] + P [Gullying] + P [Chemical Attack] + P [Sheet Erosion] + P [Wind Erosion] + P [Frost Action]

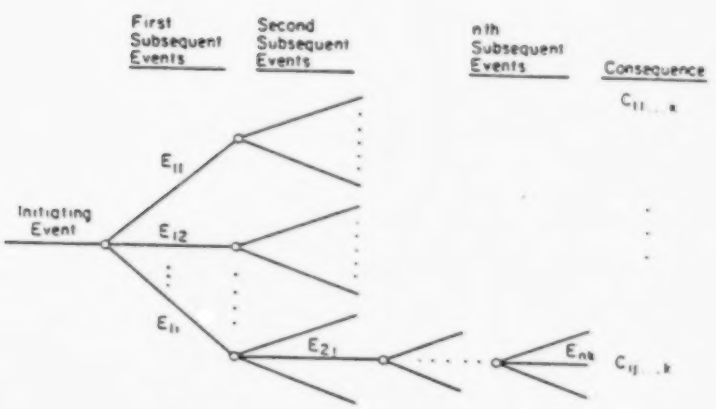
$$= 5 \times 10^{-5} + 1 \times 10^{-3} + 1 \times 10^{-5} + 1 \times 10^{-3} + 1 \times 10^{-3} + 1 \times 10^{-5}$$

$$= 3.07 \times 10^{-3}$$

Similar approaches can be followed to evaluate the other failure probabilities. It must be noted that a complete probabilistic analysis would require considerably more work than is reflected here.



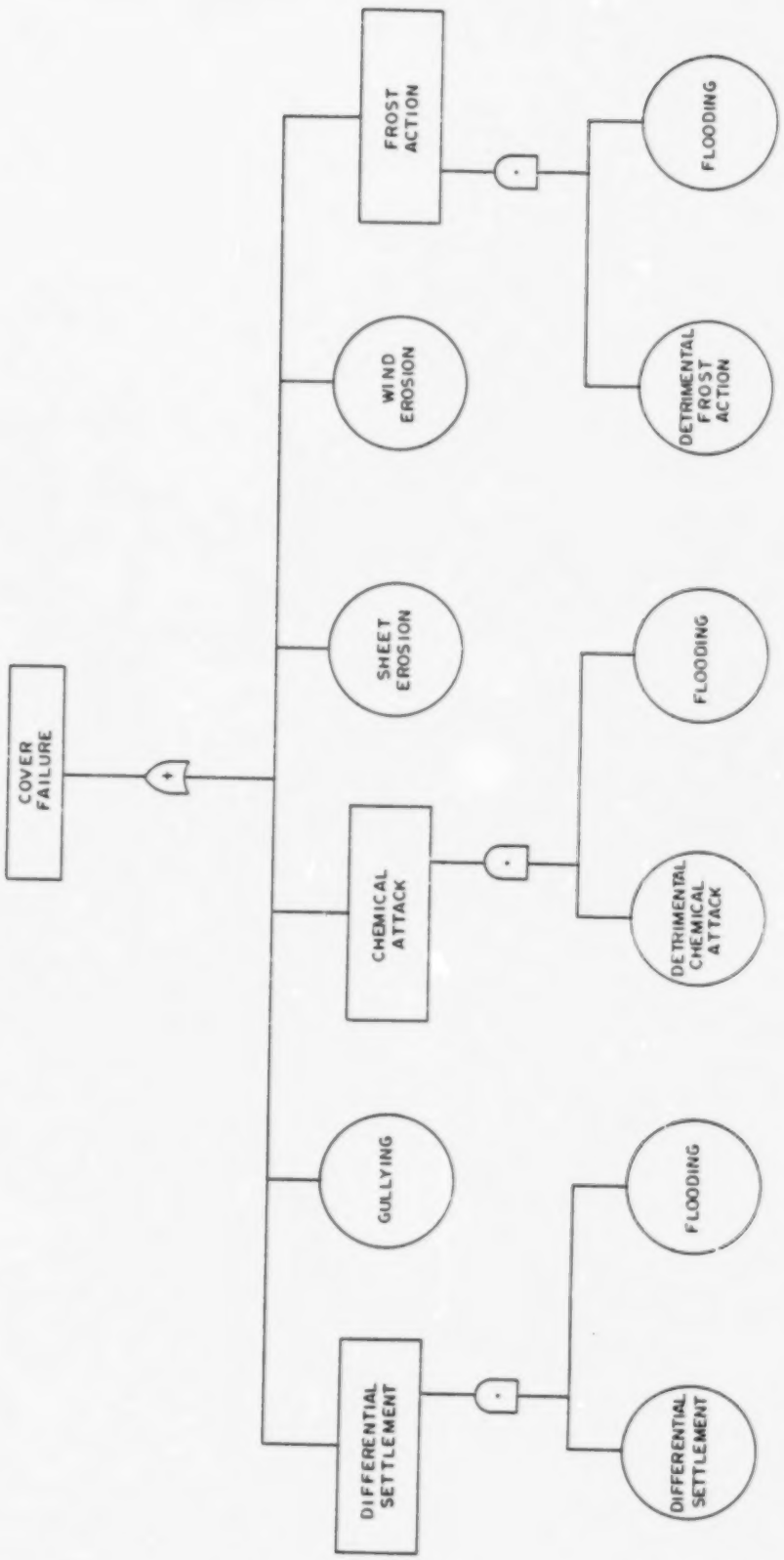
a) Fault tree diagram



b) Event tree model

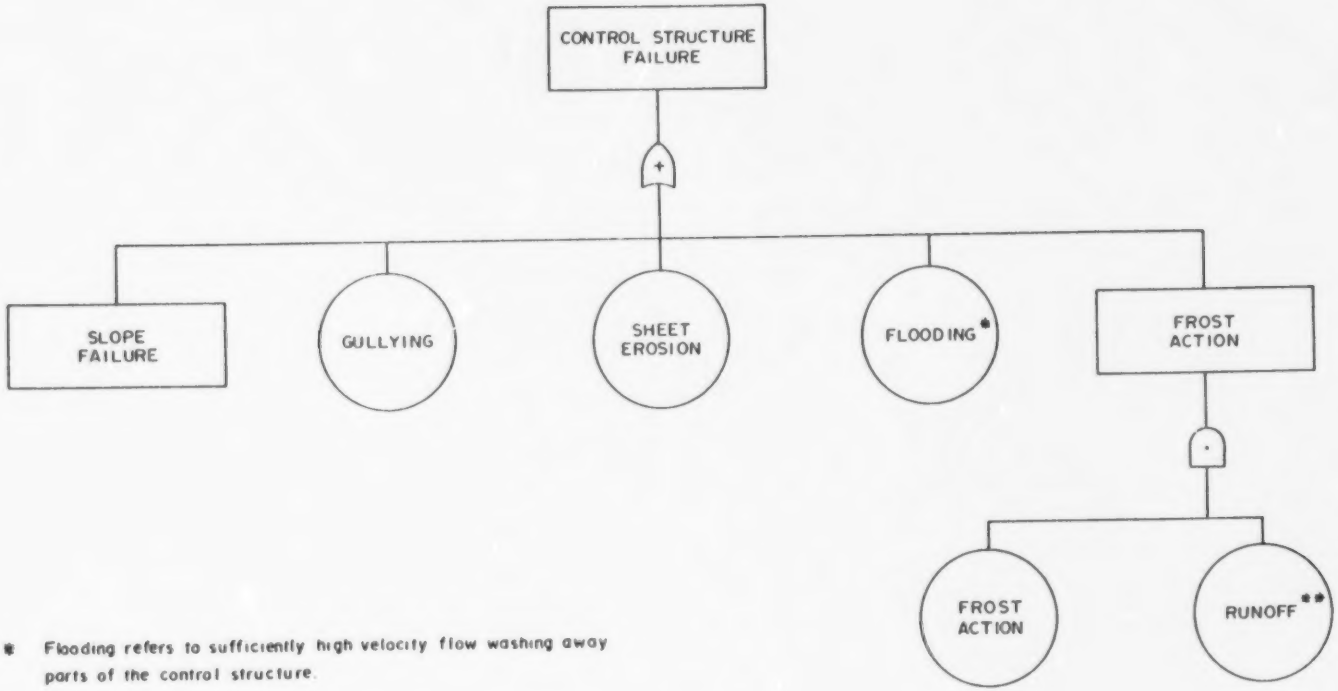
SCHEMATIC FAULT AND EVENT TREES (ANG & TANG, 1984)

FIGURE 11



FAULT TREE FOR COVER FAILURE

FIGURE 12



* Flooding refers to sufficiently high velocity flow washing away parts of the control structure.

** Runoff means flows of sufficient intensity to cause failure after disruption by frost action

FAULT TREE FOR CONTROL STRUCTURE (EMBANKMENT) FAILURE

FIGURE 13

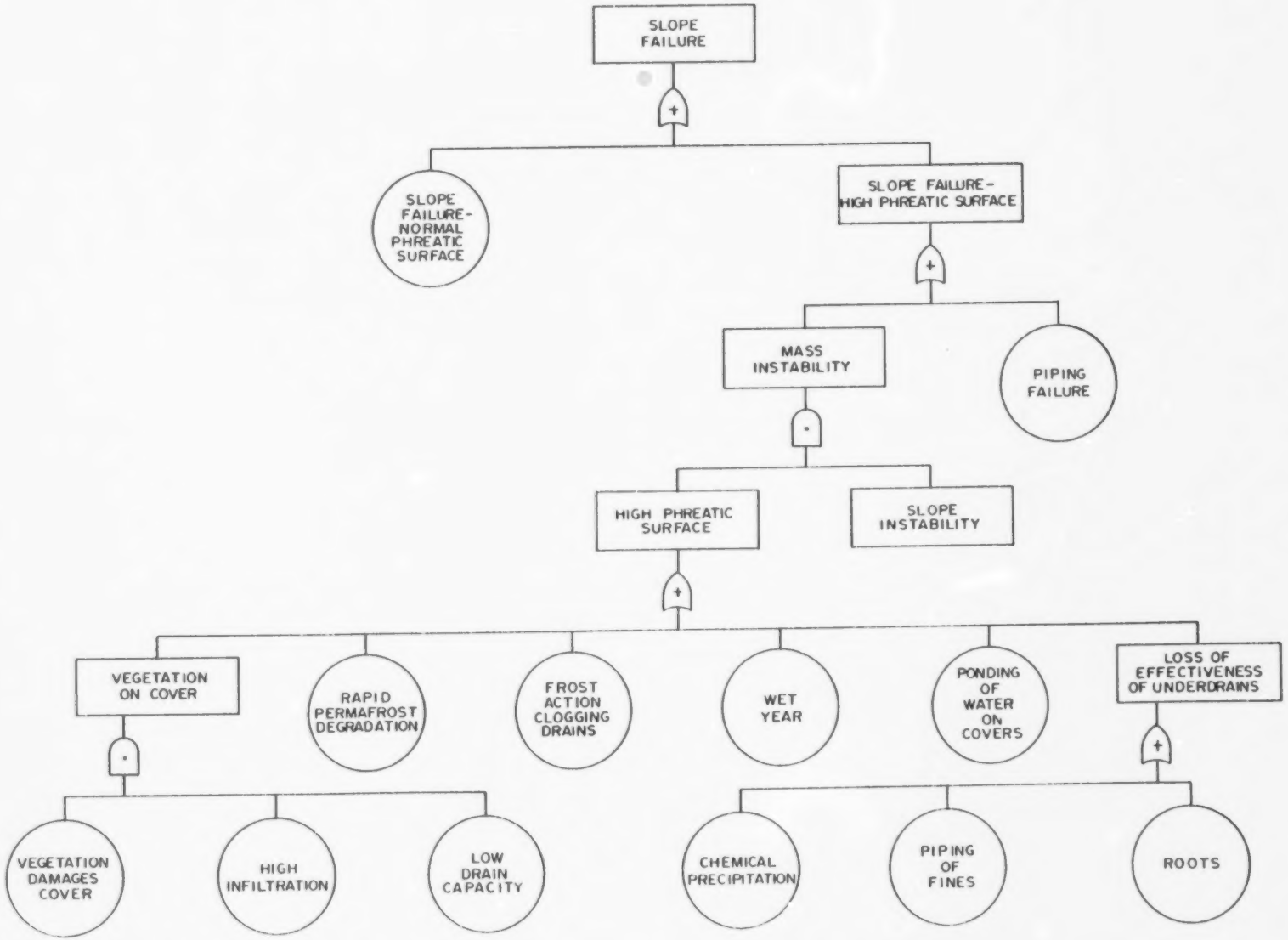
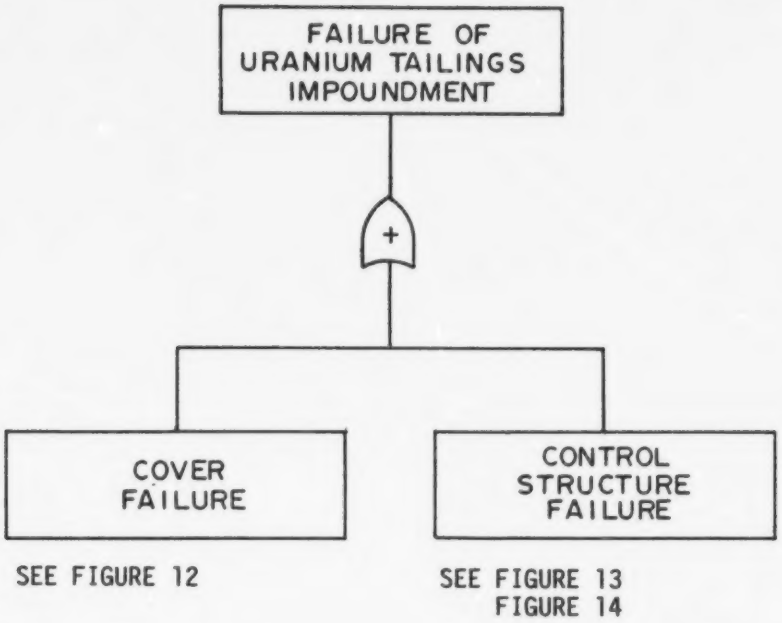


FIGURE 14

FAULT TREE FOR SLOPE FAILURE OF CONTROL STRUCTURE (EMBANKMENT)



FAULT TREE FOR OVERALL LONG TERM STABILITY OF URANIUM TAILINGS IMPOUNDMENT

FIGURE 15

TABLE 9

SUBJECTIVE PROBABILITIES OF BASIC FAILURE EVENTS IN FIGURE 12

EVENT	DISCUSSION	SUBJECTIVE PROBABILITY	HOW TO EVALUATE PROBABILITIES BETTER
Differential Settlement	- Assume that this event occurs due to large settlement caused by unsaturated flow consolidation (a problem not foreseen during design).	0.001	- Perform detailed settlement analyses, using all possible mechanisms and consider influence if some are neglected.
Flooding	- Flooding leading to dispersion of tailings following differential settlement is assumed to be associated with the 1 in 200 year flood.	0.05	- Perform detailed flow analysis as well as gully and other erosion analyses.
Gullying	- Concentrated flow causing excessive local erosion, despite good design	0.001	- Perform complete analysis following Falk, et al (1985), propagating uncertainty throughout the analysis
Detrimental Chemical Attack and Frost Action	- Consider these as unforeseen events and therefore of low probability.	0.001	- Difficult to evaluate in more detail
Flooding	- Once chemical attack or frost action has occurred a relatively small flood may cause cover failure	0.01	- Perform erosion analysis based on degraded cover
Sheet Erosion and Wind Erosion	- Consider degradation of cover with time, the probability will therefore change with time.	0.001 (assumed after say 50 years)	- Use USLE or other erosion analysis

3.0 DISCUSSION OF ALTERNATIVE STABILIZATION MEASURES

3.1 REVIEW OF INSTABILITY EVALUATION

An overall assessment of the potential for instability due to the various instability or release mechanisms is given on Table 10. In arriving at these assessments it is assumed that:

- embankments have 2 horizontal to 1 vertical side slopes
- a forest cover is established on all embankments except Dam A at the Elliot Lake site which has a heavy riprap cover
- thin soil and forest cover has been established on the impoundment surface (refer Steffen Robertson & Kirsten, 1986)

From this summary it is apparent that the main concerns regarding long term stability associated with each impoundment are as follows:

A. Elliot Lake Dam A

The embankment to this dam is considered to be relatively stable in the long term. Of moderate concern is the potential that, if a solution to acid generation in the tailings cannot be found, then acid seepage may result in iron salt precipitation and blockage of the underdrainage system.

Drainage of the impoundment is towards Dam B and there are no diversion works associated with Dam A.

With no surface water discharge and a low seepage from this embankment, the water quality of surface runoff is only of minor concern. If acid generation continues in the tailings then seepage will represent a severe instability or release mechanism in the long term. The long term stability of the grout curtain subjected to acidic seepage waters is questionable. However, if acid generation is prevented then the grout curtain should be stable.

B. Elliot Lake Dam B

This embankment is stable against most of the long term disruptive forces.

Despite the fact that the embankment is constructed of rock waste it was assessed as having a severe potential for gully erosion. This result was obtained because of the relatively small and uniform size of the rock waste. It is considered that the evaluation methodology over-estimated the severity of this release mechanism.

Seepage erosion is considered to be a potentially severe cause of instability due to the potential for the long term piping of tailings through the rock waste. Since the impoundment cover slopes towards Dam B and all the layering in the dam (because of the discharge pattern) slopes towards Dam B it is anticipated that a high phreatic surface will be maintained behind the embankment.

SUMMARY OF EVALUATION OF POTENTIAL INSTABILITY OF IMPOUNDMENT SURFACES

IMPOUNDMENT	EMBANKMENTS								DIVERSION WORKS				SURFACE WATER QUALITY		
	Sheet Erosion	Gully Erosion	Flood Erosion	Wind Erosion	Drains Plugging	Frost Action	Seepage Erosion	Physical Instability	Floods	Gully Erosion	Ice & Debris Blockage	Sediment Blockage	Without Treatment	With Treatment	Seepage
A. ONTARIO SITES															
(i) Dam A	m	m	m	m	M	m	m	m	N	N	N	N	m	m	s
(ii) Dam B	m	s	m	m	m	m	s	M	s	s	s	s	s	m	s
B. SASKATCHEWAN SITES															
(i) Wet Tailings Site	m	s	m	M	M	M	m	M	s	s	s	s	M	m	M
(ii) Semi-dry Tailings Site	m	s	m	M	s	M	s	s	s	s	s	s	s	m	s

NOTES:

(i) 2:1 side slopes

(ii) Forest cover to all embankments except Dam A which has a heavy riprap cover

(iii) Thin soil and forest cover to impoundment surface (see Steffen Robertson & Kirsten 1986)

(iv)
n - none
m - minor
M - moderate
s - severe
N - not applicable
U - unknown

TABLE 10

A moderate risk of physical instability is assessed for this embankment as a result of the anticipated high phreatic surface and the potential for seepage erosion.

The spillway is located adjacent to Dam B. This is considered to be the most vulnerable control structure with a severe potential of failure due to each of the potential failure mechanisms.

With the relatively high infiltration estimated for the cover, near surface leaching of the tailings will occur. Some of the leachates will be perched on slimes zones and will migrate towards the old pond area near Dam B and be discharged to the surface. Surface waters are expected to become contaminated by this mechanism. It is concluded that, unless water treatment is maintained, this represents a failure or release mechanism of severe concern.

If acid generation continues in the tailings then seepage will represent a severe instability or release mechanism in the long term.

C. Wet Tailings Site, Saskatchewan

The potential for instability of this impoundment in the long term is moderate.

With 2:1 side slopes, there is a severe potential for deep gully erosion. There is a moderate potential for drain plugging, due mainly to solifluction, root action and frost. Frost action is expected to induce seasonal solifluction on the downstream slope. With the potential for gully erosion and increased pore pressures due to drain blockage it is considered that moderate potential for physical instability exists.

A severe potential exists for instability of the long diversion ditch, due to each of the failure mechanisms.

Seepage water quality is expected to be poor for the long term. Because of the low acid generating potential of these tailings and the relatively low seepage rate, this mechanism has been assessed a moderate level of potential instability or release.

D. Semi-Dry Tailings Site, Saskatchewan

The potential for instability of this impoundment, as defined, is assessed to be severe.

The high erosion susceptibility of the embankment materials made it likely that severe gully erosion will occur. During periods of temporary loss of vegetation cover (due to forest fires), relatively rapid rates of wind erosion may occur. There appears to be a severe potential of drain blockage due to chemical precipitation, covering of the outlets, root action and frost action. With blockage of the underdrainage system a severe potential exists for seepage erosion of the underseal and embankment. An overall severe potential of long term instability is assessed.

While only minor diversion works are required it is considered that severe potential exists for the failure of these diversion structures due to each of the mechanisms for failure.

Because of the low permeability of the tailings relative to the cover materials, it is anticipated that contaminated water surface discharges will occur. Unless infiltration is inhibited by an infiltration barrier in the cap or unless long term treatment is provided, this represents a potentially severe instability.

Long term seepage of poor quality water is anticipated and this is assessed as a potentially severe mechanism of long term instability or release.

3.2 ALTERNATIVE STABILIZATION MEASURES

3.2.1 Sheet Erosion

The establishment of forest cover or a thin layer of rock waste or riprap is considered to provide adequate stabilization for the long term. Generally the control measures required for gully erosion will be sufficient to prevent sheet erosion.

3.2.2 Gully Erosion

Control of gully erosion can be implemented in three ways:

(i) Installation of an erosion resistant layer: Current technology does not permit a realistic estimate of the benefit or effect of forest cover, and additional research in this respect is warranted. Heavy riprap cover is the only tried and proven stabilization measure considered appropriate for long term embankment stabilization at the slopes (2:1) commonly associated with tailings embankments in Canada.

(ii) Reduction of the drainage area contributing to gully erosion: The construction of berms and diversion ditches to limit drainage areas is a cost effective measure. Since embankment slopes have relatively small surface areas the prime control is prevention of impoundment surface drainage over the crest of the embankment.

(iii) Flattening of the slope: Flattening of the slope increases the drainage area. The benefits to be gained with respect to the total depth of erosion is small. Flattening the slope does provide additional cover on the downstream slopes which allows considerably more erosion before the embankment becomes unstable.

3.2.3 Flood Erosion

Site selection to ensure that tailings impoundments are located outside the flow path of major flood flows is the most effective design measure. The use of heavy riprap or special erosion control structures may have to be considered if such siting cannot be avoided.

3.2.4 Wind Erosion

The establishment of forest cover is a prime control measure. If soils are highly susceptible to wind erosion then erosion during periods of temporary forest cover loss (following forest fires) are a concern. The use of thin layers (600 mm) of gravelly tills, waste rock or riprap provides adequate protection.

3.2.5 Plugging of Drains

The prevention of drain plugging due to the piping in of fines requires the installation of appropriately designed filter layers.

Prevention of drain blockage due to either chemical precipitation or root action may include the following measures:

(i) designing the drains and discharge such that they operate in a submerged or flooded condition;

(ii) provision of surplus drain capacity;

(iii) constructing embankments of free draining materials which would allow drainage if the drains plugged.

Prevention of drain discharge points from plugging due to sedimentation or solifluction requires discharges away from the toe in an environment where sedimentation will not occur.

Mitigation measures to allow for freezing is to discharge to drainage beds which allow lateral or upward flow under the frost zone.

3.2.6 Seepage Erosion

Seepage erosion can be prevented by using coarse, free draining soils or rock in the toe region of the slope, with appropriate filter layers to prevent the migration of fines.

3.2.7 Diversion Works Protection

(a) Floods

It is recommended that diversion works be designed to carry safely the Probable Maximum Flood.

(b) Gully Erosion

Long term gully erosion protection requires placement of heavy riprap in all areas of concentrated water flow.

(c) Ice and Debris Blockage

To prevent blockage, drainage channels should be designed with wide bottom widths and have an ample reserve of capacity which will allow partial blockage. Slopes adjacent to diversion structures should be protected by

riprap or vegetation to prevent severe erosion in the event of temporary blockage.

(d) Sediment Blockage

To prevent the accumulation of sediment in the diversion channels, consideration should be given to each of the following measures.

(i) Establishing erosion resistant covers, such as forest cover, or riprap, over the catchment area to prevent the initial development of sediment.

(ii) Install diversion ditches at gradients which promote scour and sediment removal.

(iii) Construct diversion ditches with reserve volume to allow some accumulation of sediment without failure.

(iv) Construct sediment ponds or traps.

3.2.8 Surface Water Quality Control Measures

The surface waters flowing from the impoundment site are a combination of:

(i) surface runoff, off the cover

(ii) water that has infiltrated through the cover, leached the upper layers of tailings and has been discharged to the surface again

(iii) seepage water from below the tailings impoundment that is discharged to the surface at some distance downstream from the embankment.

Control of this surface water quality can include any of the following:

(i) Placement of covers to prevent direct contact between surface water runoff and the tailings. Such covers are considered necessary for tailings which may deteriorate the surface water runoff, such as the tailings from the S.D. site.

(ii) Control of infiltration through the cover to prevent mounding of the water table in the underlying tailings, and surface discharges of contaminated infiltration water. Two alternatives exist (see Steffen Robertson & Kirsten, 1986)

  (a) Forest cover on a thin soil cover which may suffice for the Saskatchewan W.T. site and Elliot Lake site.

  (b) Installation of an infiltration barrier plus an overlying drainage layer. This may be required at the Saskatchewan S.D. site.

(iii) Control of upward salt migration by the installation of capillary suction barriers.

(iv) Control of surface water quality by the inclusion of tailings or soil modifiers or chemically active layers (such as lime) to limit acid generation or neutralize acids produced.

(v) Provision of long term surface water treatment facilities.

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